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15. FREQUENCY-RESPONSE TECHNIQUES FOR DOCUMENTATION AND IMPROVEMENT OF ROTORCRAFT SIMULATORS

MARK B. TISCHLER

I would like to pick up on a number of points that Ron Du Val made. It was a good introduction for some more of the detailed aspects, and I think it follows well with what Dave Key is going to talk about afterward. I am going to talk specifically about analytical techniques, some of which Ron introduced for documenting and improving rotorcraft simulation. This includes mathematical modeling, which Ron was addressing, and visual and motion systems, how we do that documentation, and how we tweak the model, as was discussed.

I would like to cover the background of the general topic, which is system identification, a class of techniques for documenting both the mathematical model and the implementation in the simulator. The specific approach that I have been working on and what we use at Ames extensively is the frequency-response approach. It is an input/output validation technique, but can be used to document and to validate physical models. Specifically, we are going to look at the application of system identification to a variety of validation problems. The core of my presentation is going to be a series of illustrations of how we used the technique for a number of simulators, including the UH-60, AH-64, and STOVL.

I will show you a potpourri of illustrations, how these techniques are used, how you interpret them, and finish off with a summary.

As I mentioned, the overall class of techniques is included in the category of system identification. And for those who are not familiar with system identification, it is a procedure by which a mathematical description of an aircraft, in this case a rotorcraft, is extracted from flight-test data. In this respect it is the inverse of simulation. In simulation we make such assumptions about the characteristics of the aircraft, its aerodynamics, how many degrees of freedom it has, etc., and based on those assumptions we formulate a physical model, and generate a simulation that is intended to predict aircraft motion. When all that works and the predicted aircraft motion equals measured aircraft motion, we have a good simulation.

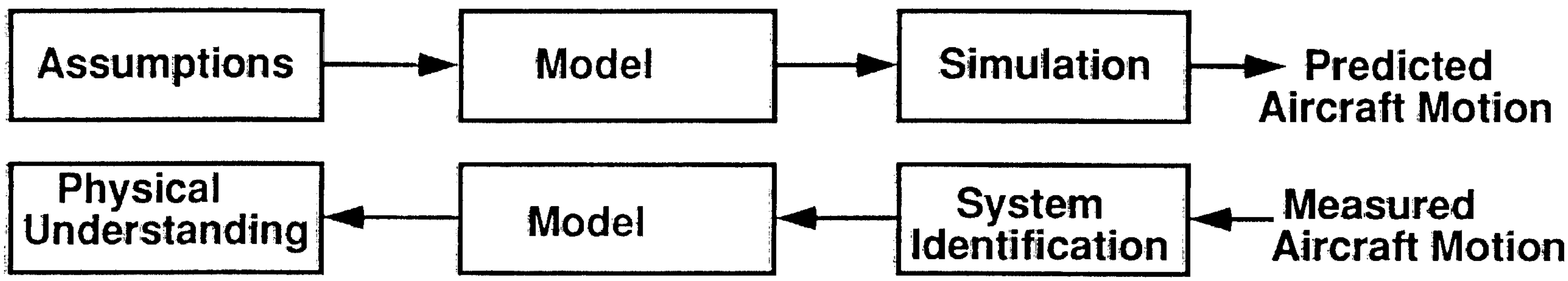
Unfortunately, as has been pointed out a number of times, that is often not the case. It is very difficult to figure out how to change the mathematical model on this end to update the simulation and make these two things match. One of the most sophisticated ways of making that happen is to work the problem in reverse. That is, take aircraft data, go out and do special flight tests for system identification; system identification becomes an inverse procedure by which one extracts a mathematical model from the flight tests. These can be physical models, transfer-function models, or state-space models. Once these models are extracted they represent the exact characteristics of the aircraft. Then they can be compared back to back with the simulation, the simulation models can be updated, and a comprehensive method is produced, by which both the mathematical models and our physical understanding can be updated. We may want to go back and change some assumptions; maybe, for example, some of our mathematical assumptions were not good.

Typical examples of the uses of system identification are given in figure 1. System identification has been around a long time, but only recently has it been adopted in a broad way in the rotorcraft community—in the last 5 to 10 years. The reason is, there are special problems associated with it that make it more difficult in some ways than a standard fixed-wing problem.

In rotorcraft there is a high-level rotor noise. The helicopter is inherently a very high-order system, so the system cannot be decoupled, unlike in fixed-wing work where only a small subset of transfers is identified. Generally, instead of having to identify 10 or 20, as many as 40 or 50 might have to be identified. There is a great degree of high-axis coupling. You have to go at least six- or nine-degrees-of-freedom, and helicopters are generally unstable machines. I am not going to go through in detail the engineering aspects of system identification (shown in

- What is rotorcraft system identification?

  - Determination of a mathematical description of rotorcraft dynamic behavior from measured aircraft motion



- What are system identification results used for?

  - Wind tunnel vs. flight test measured characteristics
  - Simulation model validation
  - HQ specification compliance
  - Optimization of automatic flight control systems

- What are the special problems in applying system identification to rotorcraft?

  - High level of measurement noise
  - High order of helicopter dynamical system
  - High degree of inter-axis coupling
  - Unstable vehicle dynamics

Figure 1. System identification background.

fig. 2). There are a lot of papers about it, papers by Ron, me, and others in the audience here. Frequency-sweep testing of the aircraft is conducted to generate a data base. Then, data compatibility is used to make sure the data are good, state-estimation is used to reconstruct poorly measured states, and advanced FFTs are used to convert the time-domain data to frequency-response data.

The frequency response is a complete description of the aircraft. It is a linearized description, but it is a linearized function of a nonlinear function. In that respect it does fully characterize the aircraft. For a lot of what we want to do, this is sufficient, because we can characterize the aircraft behavior by its frequency response and compare that with the simulation frequency response. I am going to show you an illustration of that.

In handling qualities we work with frequency responses of the system to check bandwidth. You can use advanced techniques for extracting from the frequency-response stability-control derivative models. This is important. I will show you an example in which we used such a model and actually flew it in a piloted simulation. In a number of simulations we implement a stability and control derivative look-up table as a function of flight condition. This is one way of actually generating a simulation model for piloted simulation. Finally, we want to verify that these identified models are correct by checking in the time-domain.

This is sort of the overall road map and I will not go into any more detail. Let me just point out a couple of reasons why we like the frequency-response approach for rotorcraft. First, the frequency-response technique has the advantage in that when you form the frequency-response ratio, the uncorrelated effects of process and measurements noise drop out. That is, any noise source that is not correlated to the input drops out of the calculation. And that makes identification easier. You do not have to make an assumption about the noise or you don't have to identify it. So from a technical standpoint it has some advantages, especially for a helicopter in which the data are often quite highly contaminated by noise, by turbines, or by measurement noise.

Second, you can extract parametric models in the frequency range where the data are valid. We have access to the function called the coherence function, which gives you direct measurements of the accuracy of the data. If the coherence drops in a particular frequency range, you may go out and rerun the data and go for it again.

Third, you can estimate time-delays directly, because the phase shift is a linear function of time-delay. It is very important in simulators where you want to identify time-delay. Then there is integration in the time and frequency domains. There are methods for artificially stabilizing the system; they do not work very well for highly unstable rotorcraft. Frequency domain does work well for that. All the results I will show you are for unstable systems.

Finally, we have developed a comprehensive package for the frequency-domain approach, CIFFR, for Comprehensive Identification From Frequency Responses. Application of system identification to the simulation environment in sort of a broad sense is depicted in figure 3. The pilot is going to make inputs into a mathematical model, which produces estimates of what the aircraft is doing. That may drive the visual system through its compensation, and the motion system through wash-outs and motion drives. The pilot is subjected to these cues, and they may be matched or mismatched and produce an overall percipient. The frequency approach that I'm going to talk about is applicable to all aspects of the validation process.

You can calculate frequency responses between pilot inputs and aircraft states and validate the mathematical model alone. You can look at aircraft states, to the visual system, and characterize the motion-system response, or go end-to-end and characterize the overall response. One example has been mentioned, the XV-15. We suppressed the actuator dynamics, because those delays were compensated by the visual systems dynamics, and because we knew that there were going to be extra delays in the visual system and that the end-to-end response would be okay. That is an example of where you might shift some of the delays and get the same end response. Some examples of what we have done in the past (and there are papers on all of these) are what I am going to highlight in the remainder of my discussion. I mentioned the XV-15; it was highly validated both in the time and frequency domains, and was a very good example.

I think most people involved in the XV-15 would agree that it was probably one of the best simulations ever run at Ames. The transfer of training was excellent, and most of the papers by Ron Gerdes and Dan Dugan indicate that the pilots were amazed when they got into the aircraft. The frequency-response studies that were done indicated that the validation was excellent across the whole pilot-handling-qualities range. We have done quite a few studies over the years on the UH-60. I will talk about some work on STOVL simulation. There has been considerable effort recently in characterizing the VMS

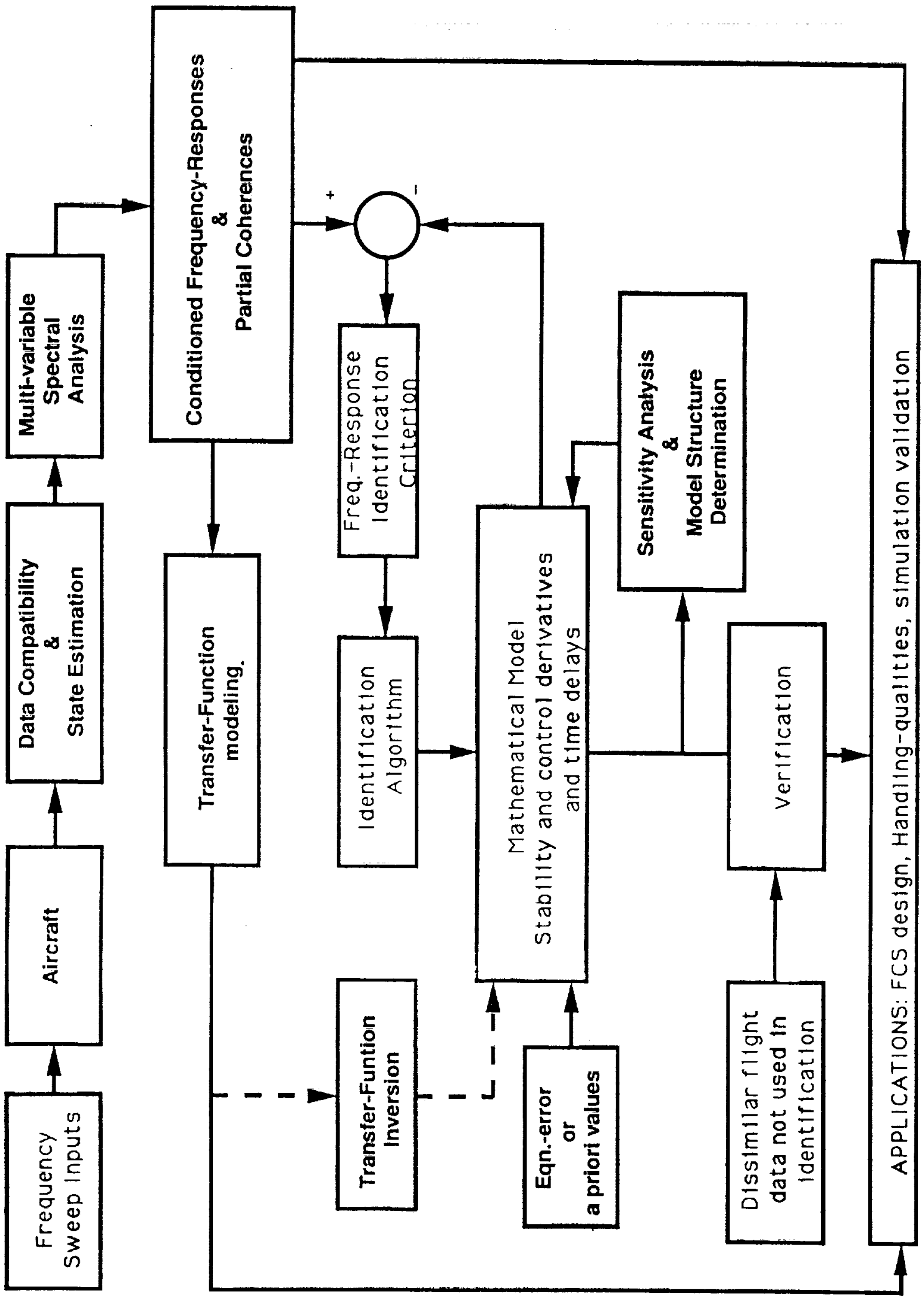


Figure 2. Frequency-response method for system identification.

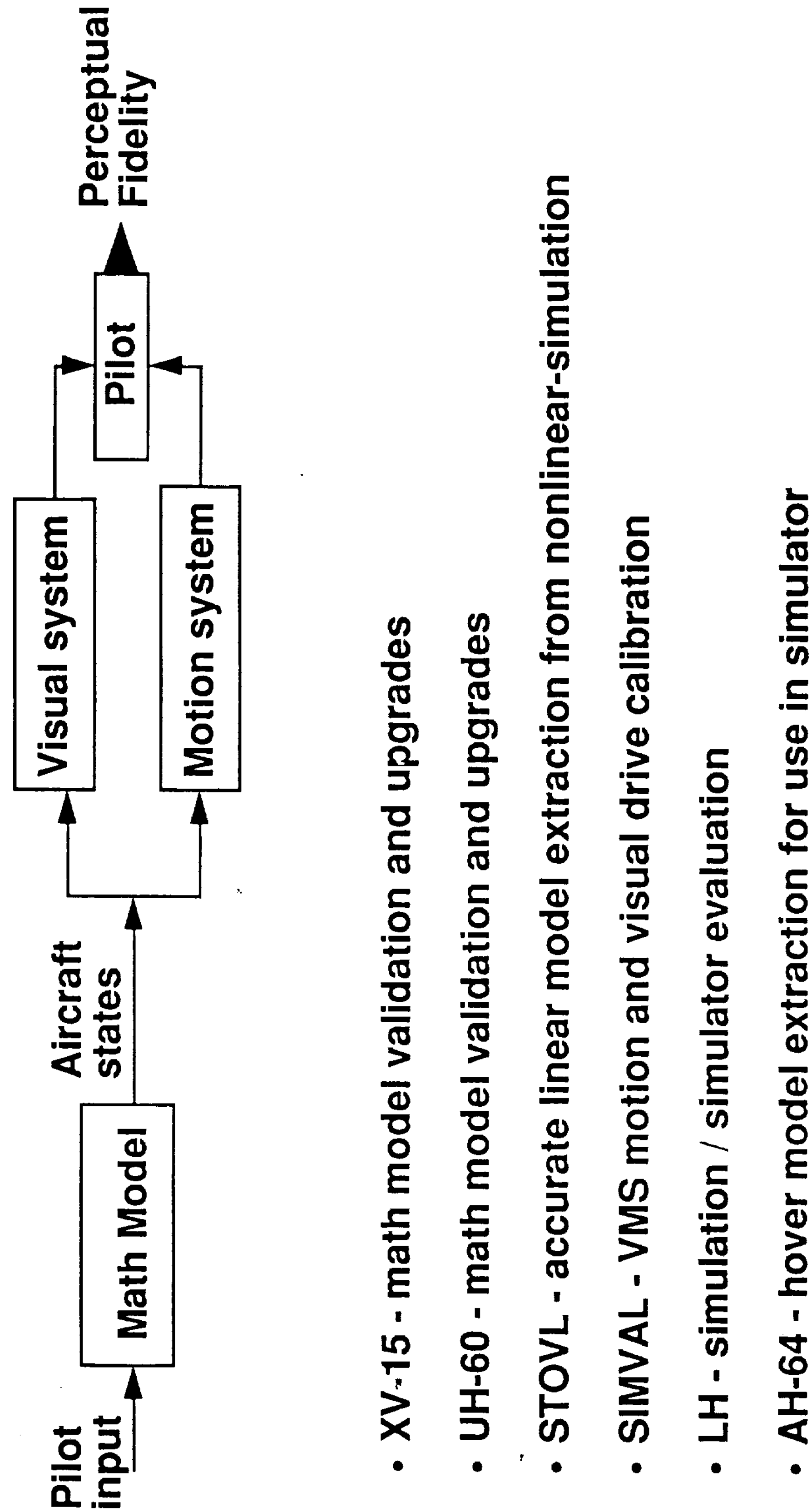


Figure 3. Application of frequency-response procedures to simulation/simulator validation.

motion base and visual systems, and I will present some results from that.

Frequency-response testing was used heavily in validating the LH simulation, both in terms of characterizing its response and of validating the handling qualities. The Army Test Directorate (AQTD) had our software in a portable suitcase and actually characterized the frequency responses in the lab. And then we have recently made, as I mentioned, an Apache mathematical model extracted from flight-test data.

The Blackhawk study that was reported by Mark Ballin at the last AHS meeting is shown in figure 4. We did frequency sweeps; here is an example. The pilot generates the inputs; we are not in favor of computer-generated input. The pilot supplies a good input. In this case we are interested in validating the simulation mathematical model. It is a physical based mathematical model— it is a blade-element-type model, very sophisticated. This is our input into the system. We use frequency-response techniques to identify input to output frequency response of the model itself, and of the aircraft. Figure 4 shows the pilot's input to the aircraft.

In figure 5, the solid lines are magnitude, phase, and the coherence function. When the coherence function is high, it indicates the data are accurate. In this case they are accurate, and include the rotor dynamics. In fact, the notch shown in the coherence-function curve is an effect of the lead-lag motion of the blades.

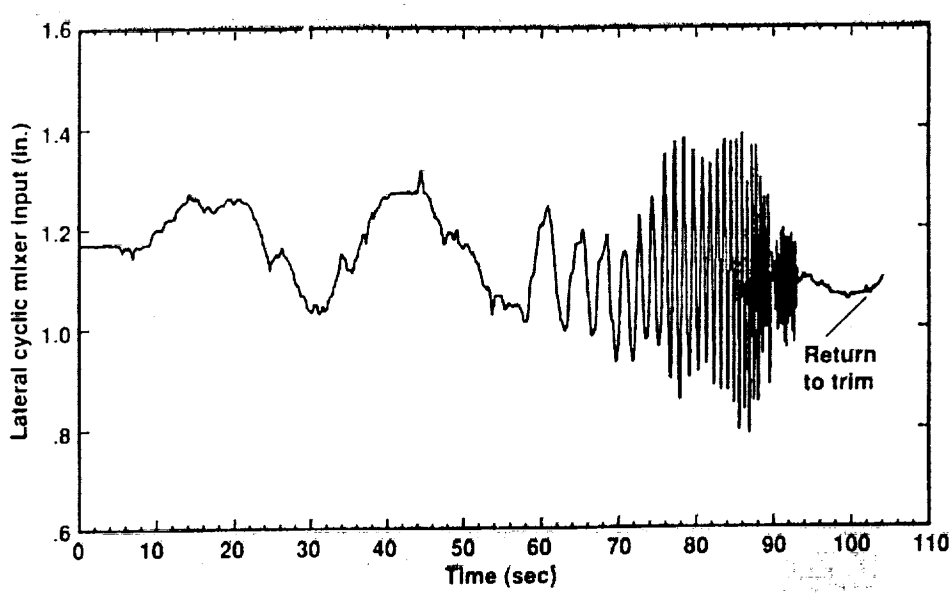


Figure 4. UH-60 Black Hawk Frequency-Sweep Flight Tests in Hover (from Ballin, 1990 AHS forum).

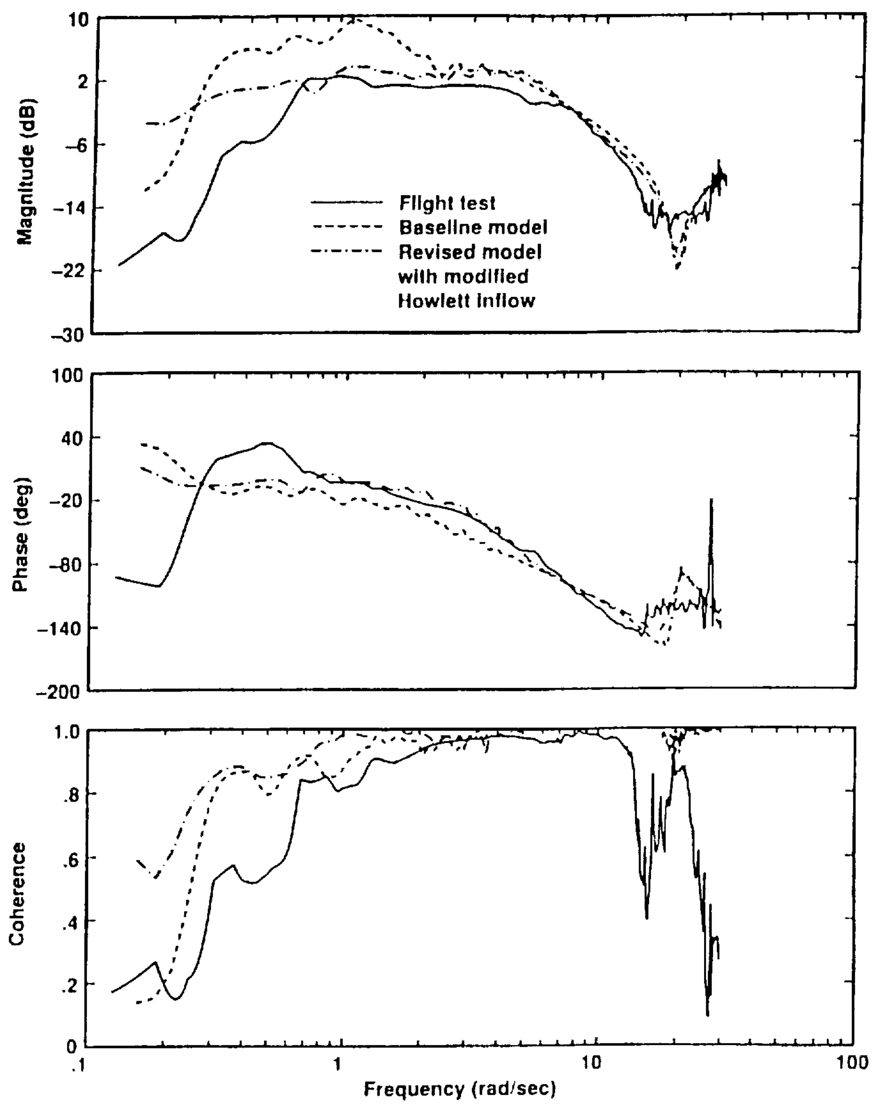


Figure 5. Tuning Howlett inflow model for improved roll correlation.

You can see that the baseline model, the dashed lines in figure 5, is pretty good at high frequency. The rotor dynamics are pretty well approximated and things look good beyond 1 rad/sec. Below that, there is quite a bit of error between the baseline model; it turns out the problems were associated with inflow dynamics. There is a first-order inflow model, referred to as the Howlett model. When the model was developed there was no way of tuning the coefficient; there were no flight-test data at that time, and this provided opportunity to collect some. By adjusting a couple of the aerodynamic constants in the inflow equations we were able to bring the model into very close agreement with the fight-test data; this response is very close to the more sophisticated, so-called Pitt Peters model; it is an example of how this tuning, which was discussed before, is done. You can get a very detailed characteristic of how the model changes by tuning the aerodynamic parameters. In this case the pilots reported a great improvement in their perceptual opinion of the characteristics of the simulator.

The next program I want to talk about is the Apache. We ran a series of frequency steps, in late August 1990. It was a very comprehensive program, with a variety of goals, one of which was to validate the AH-64 mathematical model. We have a couple of mathematical models from one of the manufacturers and one of them was developed in house. We did frequency sweeps in hover and in forward flight with the SAS off, and gathered quite a data base from that. One of the goals of the program was to extract a linear model, which was then used in the simulator to do handling qualities. In this case, the study was done to evaluate the displacement dynamics and to determine how they affect pilot handling qualities. The point is, we extracted a mathematical model and actually flew it. That was one of the first times that had been done. The hover response, SAS off, is shown in figure 6; the figure also shows the on-axis pitch response, the on-axis roll response, magnitude, and phase. The flight data are represented by a solid line, the dashed line is the model.

We identify a model that, as you can see (fig. 7a), characterizes response very well. This particular model has basic rigid bodies of freedom. It also has in it the inflow degree of freedom, and you can see that the characterization is quite good. In the time-domain (fig. 7b), the model is very characteristic of the on-axis response to pedal input, yaw rate, and acceleration, which is very good. And the dominant coupling response, which is a roll response, is excellent. So this is an example of where we took the model and drove it with these similar flight-test data; as you can see, the predictions are really excellent. The pilots reported very good fidelity (fig. 7b) of the simulation, that the coupling responses are very good, and that they are actually flying this model.

Another example is the STOVL program (fig. 8). In this case we wanted to extract a linear model. You have the possibility of generating a linear model, but you can also use system-identification techniques to do the same thing. And when you use system-identification techniques to do that, you can characterize some of the nonlinear behaviors much better.

The step input into the elevator, which is the dominant longitudinal response, is shown in figure 9. The dashed line is the numerical perturbation model. In fact, for the very beginning of the response the numerical perturbation technique is much better because it is a very small perturbation. And as you can see, it is unstable.

Our last example is a vertical motion simulator, which is a lead-in to Dave Key's presentation. Here we were interested in documenting the vertical motion simulator response, both the visual system and the model response, as well as the motion system (fig. 10). The model response—and it is an ideal, simple model—is the solid line; it is a very simple attitude system. Our visual system drive uses an algorithm developed by McFarland to buck out the inherent delay, and the resulting response is exactly on top of the model (fig. 10). He did a very nice job in coming up with an algorithm that allows the system to follow the mathematical model.

The motion command has a great deal of wash-out at low frequency, and tracks with some gain error at high frequency the motion follow-up which the pilot feels, lag at high frequency (fig. 10). The system-identification approach provides a way to characterize independently all these various effects; Dave Key will talk about how you interpret that. The point is, you go into the simulator and split out the various effects. You can see that at low frequency the motion wash-out is quite significant. The last result (fig. 11) shows a comparison of pilot workload in the UH-60 in a hover/bob-up task. Here we are looking at the frequency contents, and what I have plotted is frequency range versus the rms of the pilot stick input over the total rms.

What figure 11 shows is that most of the pilot's input—say up to about 80% of it, which is reflective of the crossover frequency—is at 2.5 rad/sec. That indicates the pilot is operating at a crossover frequency of 2.5 rad/sec. The flight data are indicated by the open circles; you can see the characteristics are almost on top of each other. In fact, the pilot ratings are essentially the same. I think they were off by one pilot rating. It is another way of using the frequency-response method to calibrate workload and to get transfer-of-training issues, because a pilot from 1 to 10 rad/sec is operating the same.

Summarizing, I think you can see that system-identification techniques are comprehensive and allow you to look at the whole range of problems. They are very well suited to rotorcraft and provide a great deal of physical insight. Finally, there are a number of computational tools out there for doing this analysis: Mathematical Lab, Control C, and CIFFR.

Are there any any questions?

MR. BRICZINSKI: I think that your implication of using this frequency-response technique primarily can be used to complement, to help analyze, simulation models as opposed to generating them. I think your techniques of system identification will generate a linear small-perturbation model. We find it necessary in your field to use a full force and moment type model. Did you suggest perhaps generating maps of stability derivative-type models that could be interpolated and then serve in a simulation technique?

DR. TISCHLER: Some of the best simulation models of helicopters in fact have been done by easily programming table look-ups at every 20 knots of perturbation derivatives. You can put in the aerodynamics and then the gravity and kinematics in a nonlinear way.

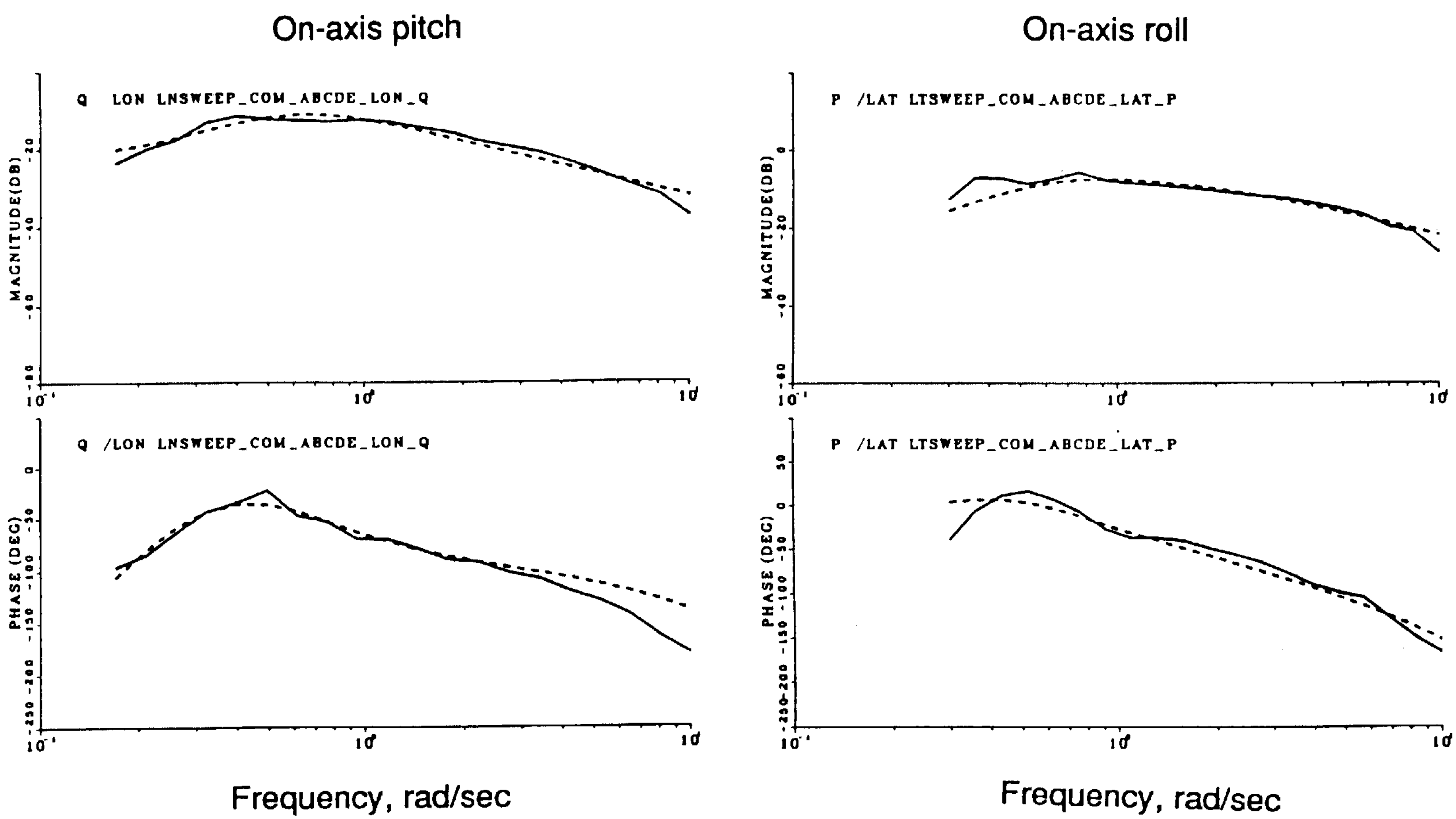
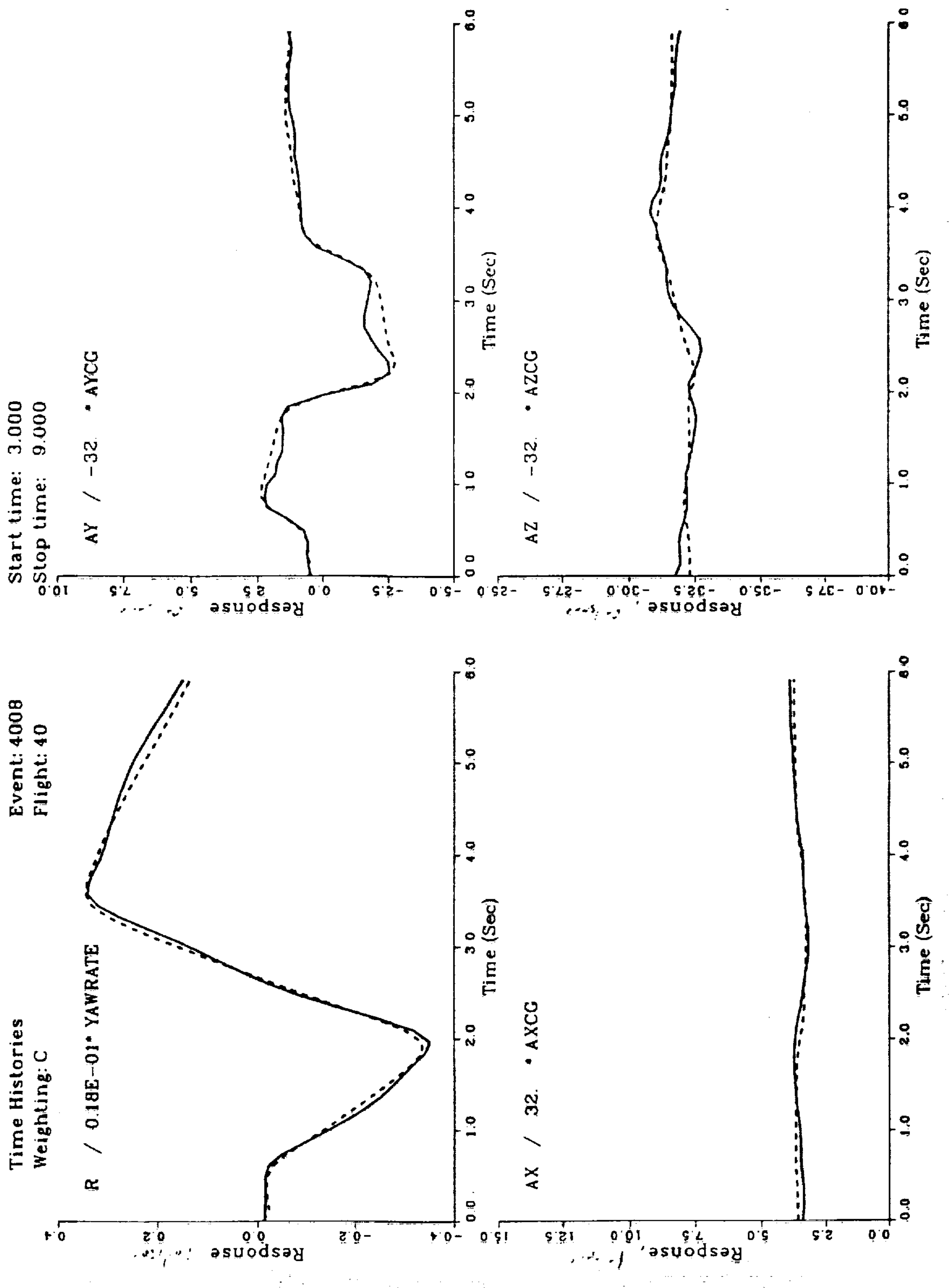
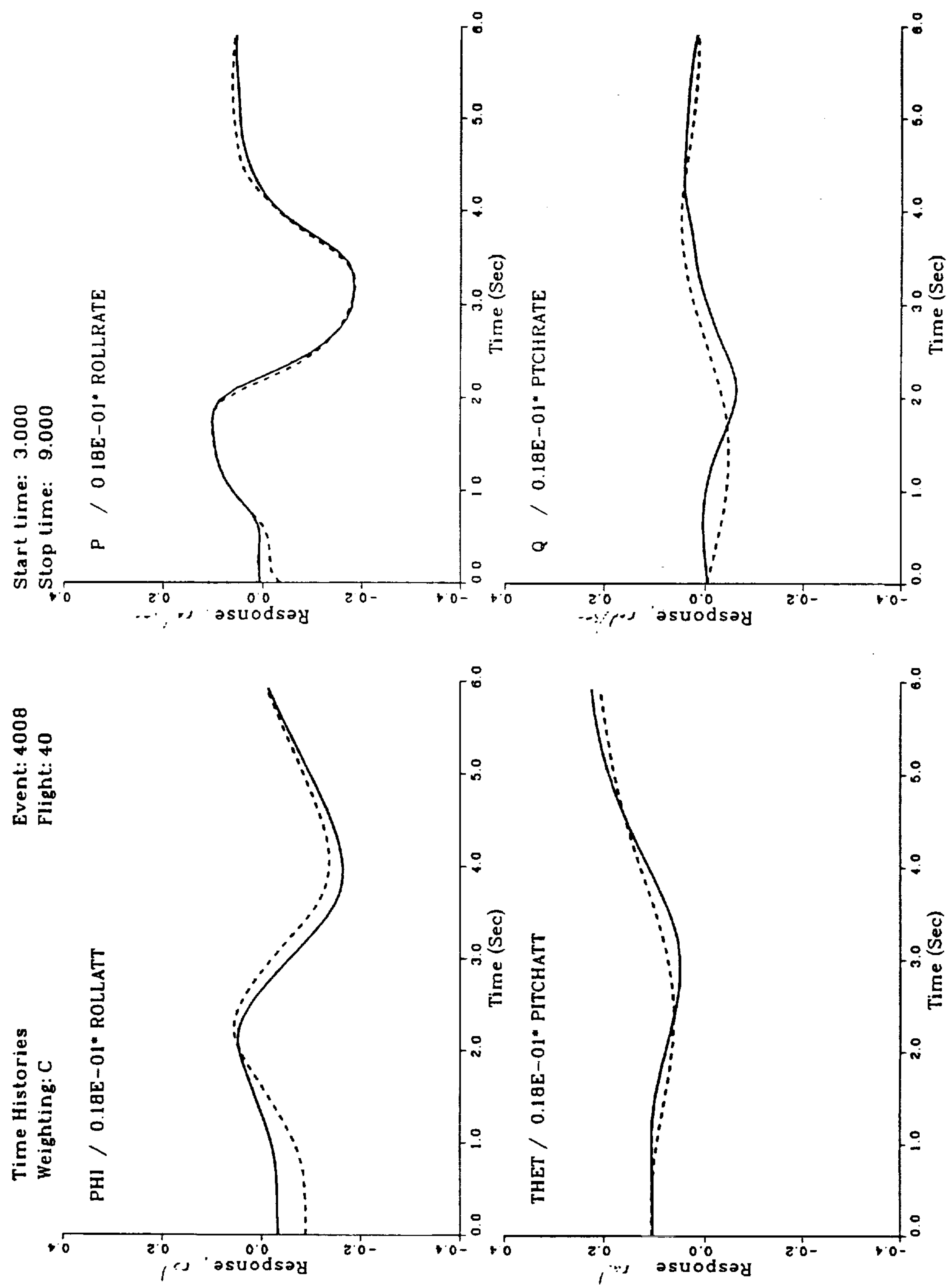


Figure 6. Identification of AH-64 hover model for piloted simulation.



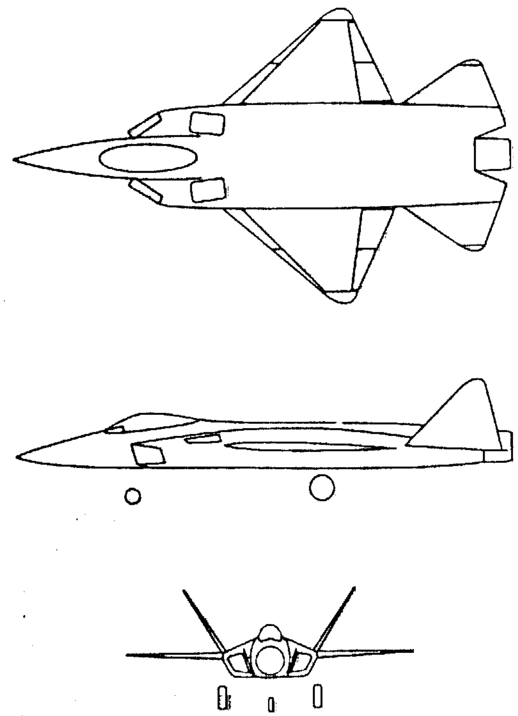
(a) Yaw rate

Figure 7. Model verification for pedal doublet.

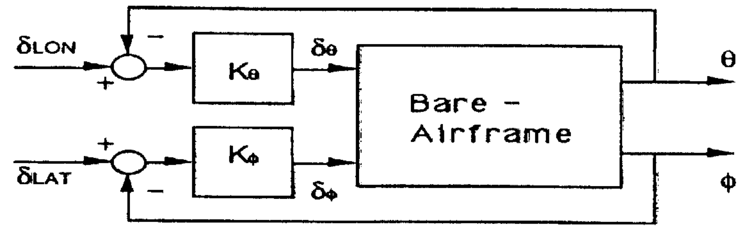


(b) Roll attitude

Figure 7. Concluded.



Identification of bare-airframe responses to δ_θ



Derivative	Initial Value	Final Value	C.R. (%)
X_u	-0.03471	-0.03602	-5.662
X_w	0.03958	0.02852	6.910
$X_{\dot{w}}$	6.764E-04	6.764E-04	......
X_q	0.2451	0.2451	......
X_{PCD}	-7.690E-03	-8.303E-03	-7.504
X_{PLA}	0.02270	0.02229	3.731
X_{Θ_N}	-0.5150	-0.5586	-2.353
Z_u	-0.04596	-0.03312	-13.62
Z_w	-0.3704	-0.2817	-4.386
$Z_{\dot{w}}$	-0.01023	-0.01023	......
Z_q	-3.754	-3.754	......
Z_{PCD}	0.1389	0.1551	5.571
Z_{PLA}	-0.3800	-0.3305	-2.254
Z_{Θ_N}	-0.01724	-0.03055	-4.646
M_u	1.661E-04	-1.059E-03	-6.016
M_w	1.222E-03	3.715E-03	5.263
$M_{\dot{w}}$	-1.286E-03	-1.286E-03	......
M_q	-0.4971	-0.6852	-5.561
M_{PCD}	0.02494	0.02818	2.517
M_{PLA}	4.993E-04	4.993E-04	......
M_{Θ_N}	2.502E-04	4.953E-04	10.16

Figure 8. STOVL linear model extraction from nonlinear RT sim (Engelland).

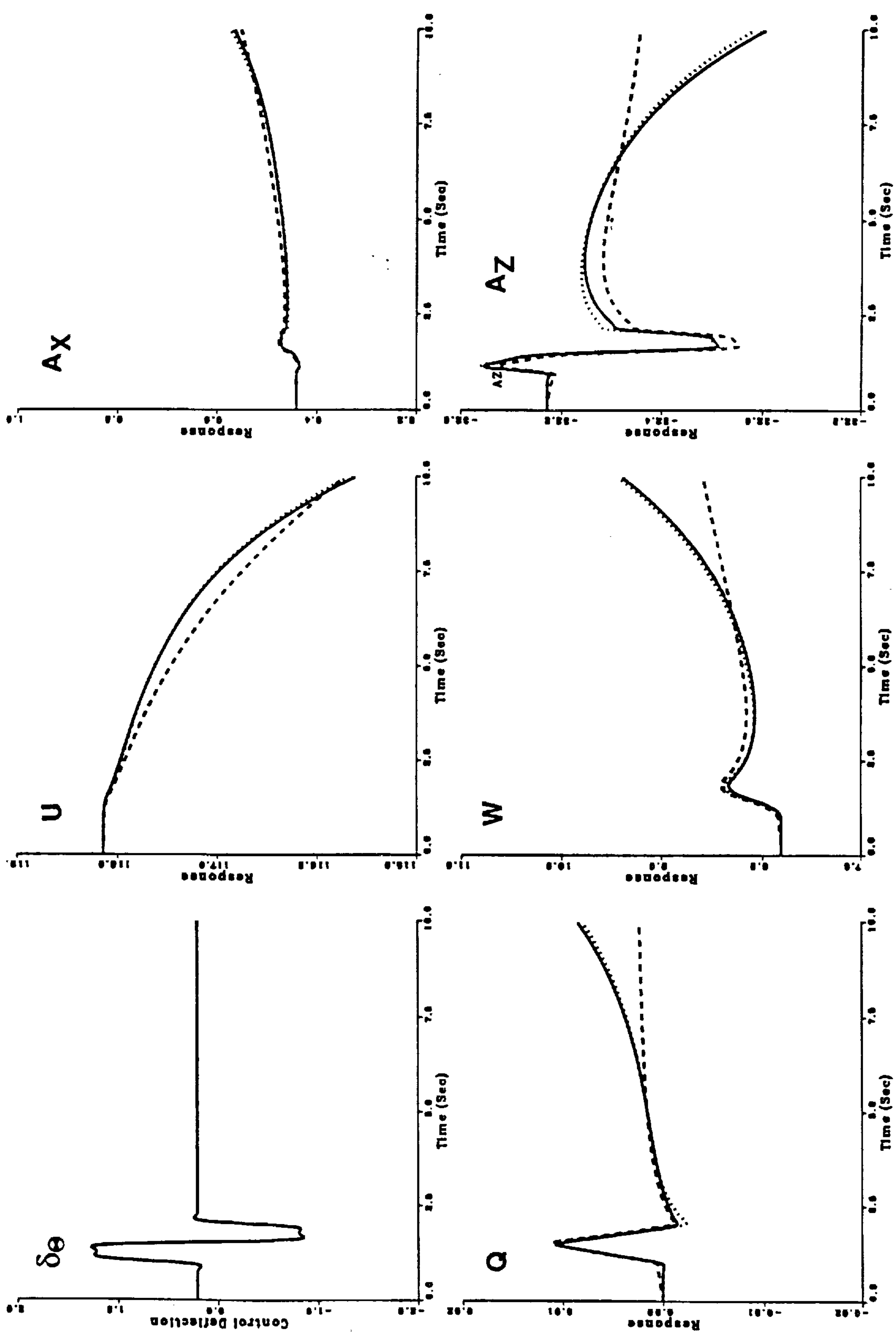


Figure 9. Comparison of time-domain predictions: numerical perturbation versus identification.

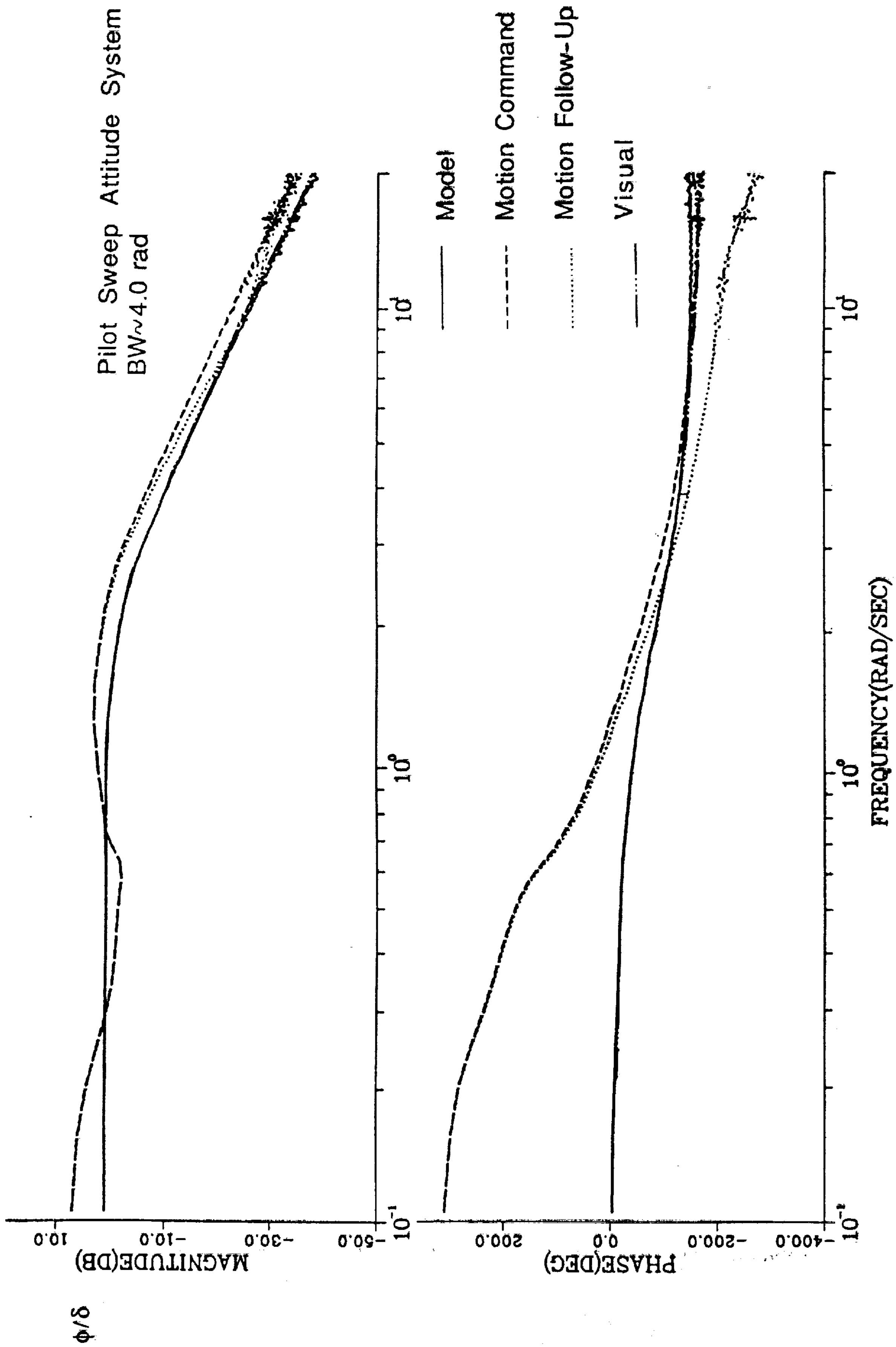


Figure 10. Documentation of vms: motion and visual systems (Atencio).

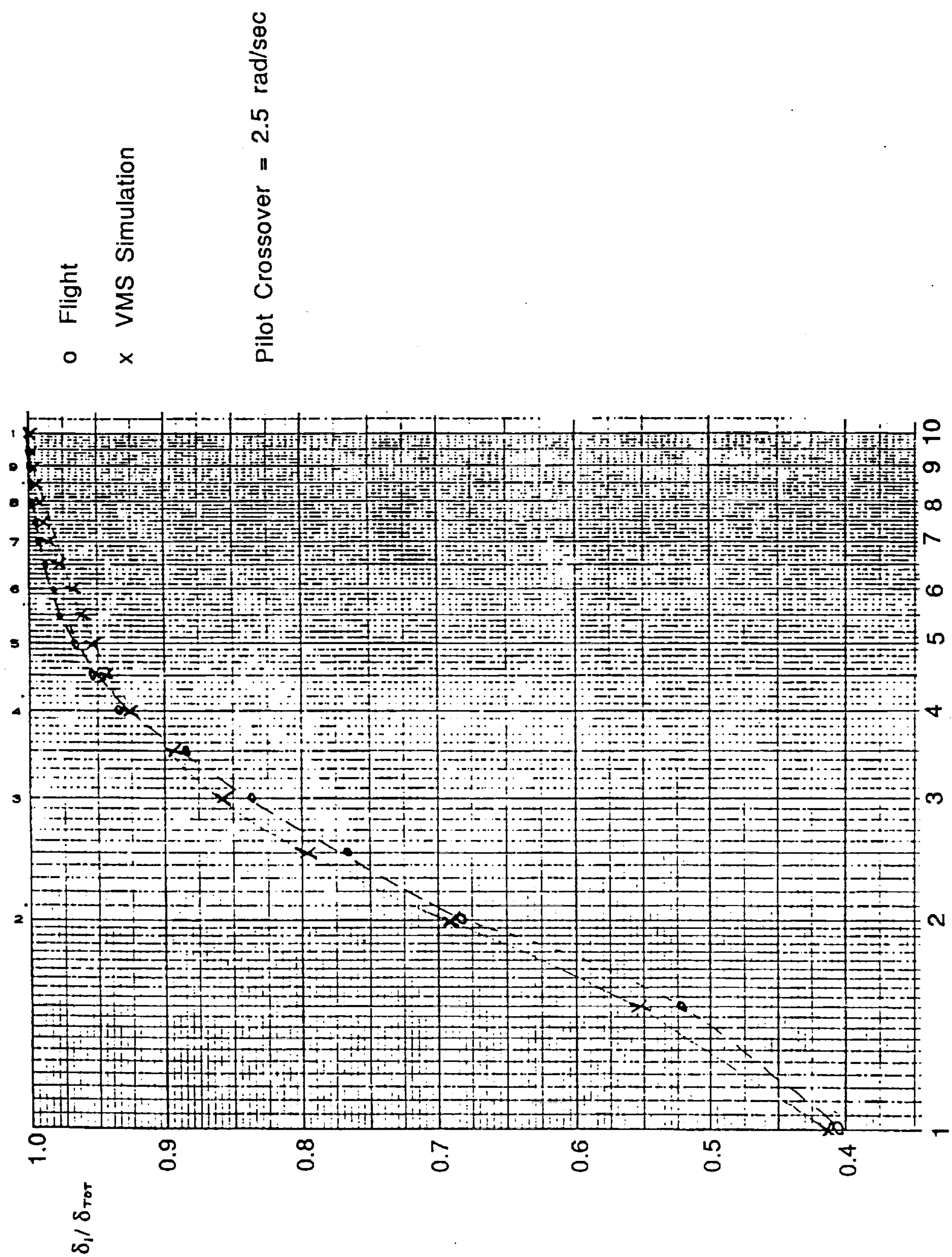


Figure 11. Comparison of pilot workload: UH-60 bob-up task (Atencio).

Of course if you are going to try to get the edges of the envelope, you are not going to make it. If you are talking about in and around the reference points, they are quite accurate. In fact the frequency sweeps, if you look at some of the papers, show pretty extreme responses. The aircraft was at the edges of its envelope and yet the linear approximations were pretty good.

MR. BRICZINSKI: We are progressing in the rotor modeling from quasi-map methods to a more rigorous blade-element method to say we are going to go where it might go for coefficient map models and take our entire aircraft as opposed to the rotor and go to quasified mapping models.

DR. TISCHLER: I am suggesting that there are some applications, for example, in this Apache case, in which we were interested in looking at the hover characteristics. We have no outside visual cues so that you are not going to be maneuvering off the edges of the envelope. You are flying on one eye and operating your hover. Clearly, it is appropriate there. The computers are now such that you can run these very sophisticated mathematical models without always making those approximations. What I am saying is it provides a mechanism for validating those, and there may be some situations in which that sort of characterization is enough. I would not say that that is generally true. Just as an example, an illustration of how you would use it.

MR. McFADDEN: My question is, do you find that small discontinuities in nonlinearities at neutral are a problem, or can you ignore them?

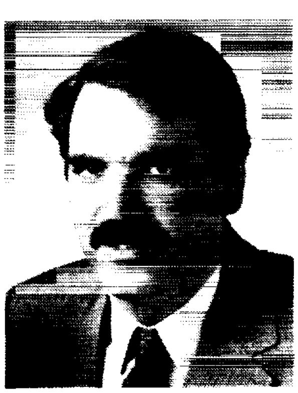
DR. TISCHLER: It depends on what kind they are. We did a characterization, for example, of the ADOCs system and it has nonlinear stick sensitivity, which is very common. If you have a small dead band and if you are operating through the dead band, that has a linear describing function. But it has a phase effect and that's a mess. So it depends on how severe they are. If they are simple nonlinearities they can be accurate.

MR. CARDULLO: There have been considerable attempts to use parameter identification techniques to identify full force and moment nonlinear models for fixed-wing airplanes and they have been quite successful. Do you have any plans to try to develop this technique for rotary-wing nonlinear models?

DR. TISCHLER: I think there is some work going on in that field. I think Ron Du Val has worked to some extent in that field. It is a very tough one because the parameters that you are talking about in a full-force model combine in a very nonlinear way and in a highly correlated way. If you look at the sensitivity of some of these parameters, there isn't any. In terms of the input/output characteristics, you need a lot of detailed inflow in the component sense. You need accurate measurements. The problem with rotorcraft is that the measurements have not been made. If you look, for example, at longitudinal response, how are you going to do a correlation based on validating the X-force when there isn't any in a helicopter?

MR. CARDULLO: SCT has been doing some work with the V-22, I think.

DR. TISCHLER: Yes. And they have done a lot of work on the Harrier. They have encountered a high level of correlation. If you start introducing a lot of effects, they found things dependent on squares and cubes of whole inputs; everything was correlated. It is difficult. You need measurements of the individual components. It can be done but it is difficult.



Mark B. Tischler is rotorcraft group leader for the Army Aeroflightdynamics Directorate at NASA Ames Research Center, in which position he is in charge of research activities in rotorcraft system identification and high-bandwidth flight control. Before joining the Aeroflightdynamics Directorate in 1983, Dr. Tischler worked at Systems Technology, Inc., where he conducted analyses of a variety of fixed- and rotary-wing vehicles. He received B.S. and M.S. degrees in aerospace engineering from the University of Maryland, and a Ph.D. from Stanford University's Department of Aeronautics and Astronautics. Dr. Tischler is a U.S. member of the AGARD Flight Mechanics Panel.