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Thanks, Bill. It's certainly a pleasure to be here. I recall with pleasure my attendance at the stall-spin workshop several years back, which I believe was mostly the same group of people. As Bill Lamar implies, I have different credentials. I maybe have one tenth of a flying hour for every flying hour that General Rushworth has. His comment about the right foot and the left foot with respect to fighter pilots made me realize all of a sudden what the control stick was for: it was so they couldn't get their feet crossed.

I would like to welcome you here on behalf of Secretary Martin, and I speak to you mostly I guess as an amateur pilot. I think I have now about a hundred hours at all types of controls, power and sailplane. I'm building a sailplane at home in my spare time, and there's the lacquer-primer-surfacer under my fingernails to prove that I'm really getting along with it. I expect roll-out any day now.

Flying is, as I think most of you who have been involved one way or another are aware, a personal experience. It is highly subjective. Some people make a lifetime career of it and are really thrown into the depths of despair when by dint of being promoted to Colonel they are taken away from it. Others, like Harrison Schmitt, the former astronaut and now senator, learned to fly and learned to fly very well for getting one thing done: to get on to the Apollo shot, and Harrison has not flown since. So people are different.

Fortunately, for pilots there is more similar than there is different about flying different aircraft. Every time I get into a new sailplane I always worry, "Is this thing going to behave strangely different from what I'm accustomed to?" Fortunately, it isn't all that different until you get going very slowly, until you start approaching the ground and you pull out the spoilers and the tail hits the ground first and you do that sort of thing. It's the secondary characteristics in which aircraft differ. Unfortunately, more people are killed due to secondary characteristics than

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due to primary characteristics: you don't stall unless you're going slowly, things like that - or unless you're in a wind shear. I think one of the things that is characterizing this flying qualities business is that you are paying more attention to secondary qualities, having gotten your arms around the primary ones pretty much with the previous specification that you put under your belt, which has been very successful. The F-16 I know benefitted substantially from having the flying qualities criteria around, and other aircraft will also.

We're now entering an era, as Bill Lamar implied, in which digital fly-by-wire (though of course the F-16 has analog fly-by-wire) is the coming thing, not for the reason that everybody wants to have a computer, but because digital systems, once you get the interfaces hooked up, are much more precise than analog systems. They do not get out of adjustment. The software, if it's wrong, stays wrong until it's fixed, but if it's right it always works (which is no great satisfaction to a lot of people). We're also, with this digital fly-by-wire era, entering a situation in which no particular relationship need hold between the controls and the response of the aircraft to those controls, which says that you've got a clear slate as far as the things that you can do with the airplane. On the other hand, you must have certain constraints, or else the guy who flies the thing isn't going to know what is going to happen when he moves the controls. So there's a very delicate nuance between retaining the control response that one expects out of an aircraft and providing some of the special modes in which the aircraft may fly up, down, or sideways.

We're also entering, of course, an era in which many aircraft (particularly fighter aircraft) will have more useable dynamic degrees of freedom than in the past. Of course, we've had flaps and slats and various things for a long time, but we have not had anything other than primary controls for the three axes of attitude control which could be operated in a dynamic way, that is, swished back and forth. Let me tell you a funny one. When I first rode on a T-39, which is approaching four years ago, I wasn't aware that the slats were automatic. When we were taking off, just about the time of liftoff this thing started going like that (shaking) and I

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said, "My God, what kind of a pilot do I have up there that his hand is moving that fast? I need someone with more experience than that." It turns out that the wind was doing that, not the pilot.

By the mere process of putting control surfaces on both ends of the aircraft we create a CCV or an AFTI, and enable ourselves to get both direct lift and direct side thrust, and by putting enough of them, or by putting big brakes out there, we can get direct stopping or nearly so. There's a considerable amount of debate as to how much of that, putting on the brakes, one wants because there's a school that believes in the energy maneuverability theory where energy is money in the bank, and the more drag the less energy, and so on. We have not sorted out, I think it's fair to say, the relative importance of being able to slow down in a hurry versus maintaining your speed. There has been some work with Harriers in which the Harriers have escaped from faster, more maneuverable aircraft by the process of cranking the nozzle down, and I think you can crank it slightly forward if I'm not wrong, and essentially slowing themselves down or lifting not straight up, but having an unexpected rise in the position of the aircraft as compared to a guy who is flying along behind them. Some of this, putting control surfaces on both ends is bound to remind someone of what they did when they first built aerial ladder trucks for the fire departments. What they did is they put a tillerman on the back end, and he steered his end and the other guy steered his. I think the stage of the game we're at with CCV's and AFTI's and such is probably pretty much at that primary point. We don't have a two-man aircraft with one guy steering the empennage and one guy steering the canards, but it is not developed terribly much farther from that in terms of where it will get to be.

Despite all of our technological advance, some things remain inadequately understood, particularily high-angle-of-attack behavior in which one always, when one buys an airplane or picks up an airplane, looks at the book and looks at the little section entitled "Spin Recovery Techniques." It will often say "spin recovery is normal" which does not give much confidence to someone who is flying an airplane that is said to have viscious spin characteristics for the first time. There are people who argue that

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the best technique is to push the opposite rudder hard over until all rotation stops and slowly but purposefully push the stick forward until flying speed is obtained, being careful that one does not exceed redline speed in the pullout. If one is having an incipient spin at 500 feet I don't think one has very much time to go through that "slowly but purposefully" type of deal, and one doesn't have time to bail out, either, at least in the airplanes I fly.

So there are things that are by no means well understood. Whether indeed we will get our secondary characteristics, high-angle-of-attack characteristics, really worked out to the point at which the pilot will have a sense that he is in control of the aircraft through a much wider range of maneuvering than he presently does remains to be seen, and I mean the average pilot, not the test pilot: test pilots for the F-16's and such can put them on their tail and skid along with the thing at 55 degrees, and I think have a pretty good idea as to whether it's going to fall off to the side; but your average pilot is going to be told to stay out of such regimes because he won't really know what to do when he gets into them, and he won't have a spin chute in the back in case he runs into trouble. I think we can probably improve in that situation because if we have more control surfaces we will have more control area, and control surface area has a lot to do with getting out of trouble, so there will be new things to learn with the six-degree-of-freedom aircraft about their departure characteristics.

The digital flight control system business is really part of a larger movement, a movement that spans the whole area of the aircraft business. In the avionics area, which I'm sad to say is distinguished from the flight control area and from the power area (mostly by barriers of Laboratory or divisional or branch separation) digitalization is taking place at a rapid rate for several reasons: one, the natural precision of digital systems; and secondly, the great flexibility one has in changing the systems if one finds that they are not right. However, with change comes the opportunity to make change that is not needed, and that is one of the things that happens when you set up a hundred man programming group to support

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an airplane. We have to learn how to control ourselves there. The digital flight-control system business offers opportunity. One of the reasons I'm telling you about these things, which are sort of ahead in the game, is that as you develop a new flying qualities specification it is very worthwhile to keep in mind what's going to happen next so that as you make definitions, as you establish criteria, you can say, "How will that apply if there is one more degree of freedom?" In other words, you very often find yourself in the position of (if you don't think into the future) establishing something that you'll have to change completely because it will no longer be valid, whereas if you said it a different way or established a criterion in a different way it would apply despite the addition of new technology. For example, digital flight controls afford the opportunity to make the controls non-linear as far as the response of the aircraft to pressure or motion of the controls is concerned, and this has been used. I believe the F-16 has sort of a quadratic or a segmented quadratic roll rate in response to sidestick roll pressure. People who talk about non-linearities in the flight-control system, however, I think are careful to leave them at the pilot-control interface, and not crank them down into the guts of the servomechanism, digitalized or analog, which is their interest in making sure that they haven't put any instabilities into that thing as far as they're concerned. If the pilot wants to have pilot-induced oscillations because of the way the controls work, that's his problem. So it figures that as you introduce non-linearities on purpose into systems you are going to have to be responsible for characterizing their effect on the linear or non-linear pilot - and not just the experienced pilot who can quickly size up the situation, but the low-time pilot who's transitioning to the aircraft. I noticed that although we apply this quadratic type of thing to the roll, we don't do it to the pitch, because the last thing anybody wants is to have a pitch that goes crazy if you push a little too hard forward or push a little too hard back; you don't want your g's to come on in a big hurry. People like to have linear g versus stick force; they've been happy with that. I think they know what it feels like. We also don't do it in yaw; I think the main reason is that people in jet airplanes don't use their feet very much, except in landing events

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occasionally, and some squirrelly maneuvers, I suppose, trying to keep the thing from sliding off in the wrong direction. But I'm not sure that most jet pilots really do practice using their feet very much, so maybe it's a matter of "don't care." The assumption always is that if there is a nonlinearity of any sort the pilot is able to compensate for that. You are giving him a total credit, which is right, but you're also giving him perhaps an additional job which you should assess as to whether it's good or bad. I think the business of nonlinearity in roll is very similar to the nonlinearity in steering a car where you don't have to turn as far to get the last bit of lock as you do at the middle, so it makes a lot of sense.

The pilot as a servomechanism has been modeled to some extent by the Aerospace Medical Research Laboratory. The thing that most impresses me about their results is "by golly, he's got a certain linear servo-type of thing with a very nice cutoff frequency characteristic and, by golly, you better not build a system which with that pilot in that loop is going to have an instability problem." I haven't seen anybody who has looked at these models of the pilot (it may be done because there are people doing everything down in the works), and added the pilot's phase characteristic and amplitude characteristic to that of the rest of the system and said, "What are the likelihoods of pilot-induced oscillations?" We don't really know what is best in the way of handling qualities. I don't know what you guys think of as flying qualities versus handling qualities; somehow handling qualities implies subjective character, the flying qualities as reflected to the pilot. The airplane may fly fine, but to the man who's handling it, it either handles nicely or it doesn't. We think that in calibrating an aircraft or in measuring an aircraft subjectively, the "fussier" the adaptation of the pilot to the aircraft, the less good the aircraft is deemed in terms of a "pilot's" aircraft. While I'm not one to cater to any minority group such as pilots, nonetheless, they've a lot of other things to do, and if the airplane is a dog to fly, they're going to spend more of their time flying the airplane than they really should. On the other hand, if you take away all the feel of the airplane, there are certain things that they're not going to be able to do in terms of

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maneuvering that aircraft, and this is part of your job, in the next years: to try to understand better, through simulation, through varying the parameters in some of these fly-by-wire aircraft.

The digital flight control system lets us build in limits to control authority, and one of the things that we still have not answered and cannot really answer at the moment is, "Should we build in these limits so that the pilot can't hurt himself or the airplane if the sensors on the aircraft know that he could do it?" In other words, should the thing absolutely come to a stop before he wrenches the wings off or should the pilot have to limit himself in some way? I think probably the answer is that if we can build the digital flight control system so that the pilot can throw the thing around at will, that it's better. In other words, if it can be accurate enough that he can get as far out as it's safe to go, we ought to let him do that, but the trick is in determining how far out is safe. This is a question that we have to answer, obviously, in the fly-by-wire systems.

Another area which is principally of concern in the Navy is the vertical take-off and landing business, which established brand-new limitations on what are normally thought of as aircraft. Obviously, the stability criteria of the Harrier when it is in a situation in which the wing is not doing very much lifting are totally different from the stability criteria when the thing is flying forward, and you've got the stabilizing airfoil lift; and from the rash of accidents with Harriers which was explained as low-time pilots it is certainly evident that it is not a terribly simple airplane to fly. It's not at all clear that this handle that cranks the nozzle down is the most ideal way of changing the direction of your thrust, or is in any way related to how the pilot would think if he thought of cranking the thrust down. It is obviously a difficult problem. Each type of vertical-takeoff and landing aircraft has entirely different stability criteria depending on where its thrust is, and where the thrust-carrying things are, and God help us if the engine fails, but we mostly watch the Navy in that area.

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Probably the most interesting area to me is the area of six-degree-of-freedom aircraft. This is a term which we blithely use to describe an aircraft which has got as a minimum some canards that can twiddle the front end of an airplane and a speed brake that can slow it down so that you get all three attitudes and all three displacements - not necessarily perfect displacements; you may not want perfect displacements, but nontheless perarately controllable actions. Clearly, having separate controls on the forward canards from the tail would provide a situation like the aerial ladder where the guy has two hands, one running the front and one running the back. We're smart enough not to do that. We have thus far, I think, with the CCV vehicle, put direct-lift function onto a thumb-switch on the good old control stick, and of course, the control stick by my count has at least five other functions on it, so it's not at all clear that that is the place to put additional functions. I keep wondering whether with the six-degree-of-freedom aircraft we might come up with a more subjectively realistic control thing in which the control stick has more degrees of freedom than does the one that we presently use, in which you could both push it to one side and twist it. I'm not sure that the muscles in the hand and the arm are up to doing what you would have to do in order to control four degrees of freedom with the one stick, but certainly there are some combinations that have to be looked at in terms of getting the most natural ability to fuselage aim or to slide nicely to the side, which is done with the feet - and I think that's probably pretty natural because people are accustomed to doing slips and yawing the airplane, and that comes naturally. The pilot workload is critical: if the six-degree-of-freedom aircraft requires more concentration on the part of the pilot to do his job it's obviously going to be less successful in the sense that in watching out for missiles, other airplanes, and so on, there won't be as much time and concentration for that.

The business of multiple modes is obviously something of much importance in a fly-by-wire aircraft, particularly six-degree-of-freedom aircraft. I'm not at all sure that we have optimized what these modes are: constant-attitude modes, fuselage-aiming mode, whatever. We seem

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to be guided more by past history in autopilots, which I don't think is pertinent, because autopilots really are long-term things where you adjust the knob to make a turn, and there are no real fast dynamics, whereas the six-degree-of-freedom controls are only to be used in a high-dynamic situation: aiming to the ground, following another airplane, and so on. If you take, for example, the most extreme case of six-degree-of-freedom aircraft which has integrated fire and flight control where you are trying to do aerial gunnery against another aircraft which you are chasing, and there's a radar that can tell you where the other aircraft is (or a laser) and there's a radar that can tell you what range it is, what then does the pilot do in that aircraft if there is servo system that can follow the other aircraft around? One of the answers, of course, is that the only thing that those sensors can't do is to tell what the banking characteristics of the airplane you're chasing is, in other words, whether he's going into a bank, whether he's going to turn. Obviously, then the pilot is the good sensor of that, and you want to hook him up to the controls so he's able, possibly with some lead functions or whatever, to do what he can do best, in order to couple the automatic part of the system to the manual part.

So there are some very challenging jobs ahead. I think we must always apply a final criteria: does the pilot feel that the airplane is doing a capable job? Will it do what he needs done? If the answer is not "yes" on that (it's partly subjective, admittedly) then I don't think you've succeeded. I'm reminded of the rather silly thing which is nonetheless true: the public response to two automobiles with the same engine, one with a light spring under the accelerator and one with the heavy spring under the accelerator. Everybody says that the one with the light spring is the more powerful car. If you can figure that out, you can probably figure out the airplane business, so I hope you'll carry on successfully here today. Thank you.

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