Comment on "Controllability Limit of a Human Pilot"

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THE experiment discussed in the recent paper by Washizu and Miyajima[1] of the University of Tokyo is quite similar to one performed in 1960 by this writer at the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, and reported in Ref. 2. The purpose of this commentary is to present a critical comparison of the results given in Refs. 1 and 2. First, a brief discussion of the two experiments is necessary.

Both of the experiments investigated the limits of manual control of unstable, second-order dynamic systems. Reference 2 considered only those systems having an oscillatory transient response, whereas Ref. 1 also considered those having one divergent mode as well.

Compensatory displays were used in both of the experiments. That is, the display showed only the system error in both of the cases. Schematically, both of the systems were of the single loop form, as shown in Fig. 1, although Ref. 2 presents evidence that higher forms of human operator adaptation are possible which invalidate this conceptual model.

The experiments differed in that those of Ref. 1 required lateral manipulator motions, whereas those of Ref. 2 were longitudinal. It is probable that this would not produce large differences between the two sets of experimental results, since, in either case, the biophysical systems involved are quite similar in detail.

Grossly different testing methodologies were employed, however. The experiments reported in Ref. 1 used only an initial transient system input and required that the operator maintain stable control for 20 sec. Substantially no practice was permitted. Only three trial runs were made for each combination of controlled element parameters tested.

On the other hand, the experiments reported in Ref. 2 used a random-appearing system input and required that stable control be maintained for 2 min. Controlled element dynamics were varied incrementally from the easier to the more difficult control problems. The subject was permitted as much practice as required. Nearly 900 trial runs were made in establishing two controlled elements believed to represent limits of manual control.

The experiment of Ref. 2 was devised in order to examine the validity of a speculative, theoretical prediction of the controllability limits given in Ref. 3. The predicted limits of Ref. 3, together with the experimental limits and revised predictions from Ref. 2, are shown in Fig. 2. Typical experimental results given in Ref. 1 are also shown. Only the oscillatory controlled element is considered.

Obviously the limits of control as given by Refs. 1 and 2 disagree widely, particularly at higher values of controlled element natural frequency (stiffness). In the opinion of this writer, the data of Ref. 1 fails to correlate with the data and predictions of Ref. 2 mainly because, in the experiments of Ref. 1, the operator was given little practice. As mentioned, 900 trials were required to obtain the two experimental limits given in Ref. 2. It is unreasonable to expect that an essentially naïve subject can duplicate these physiological limits without substantial training.

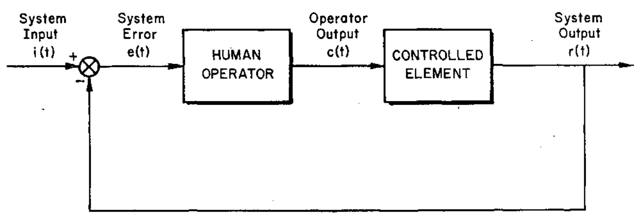

Fig. 1 Block diagram of single loop compensatory manual control system.

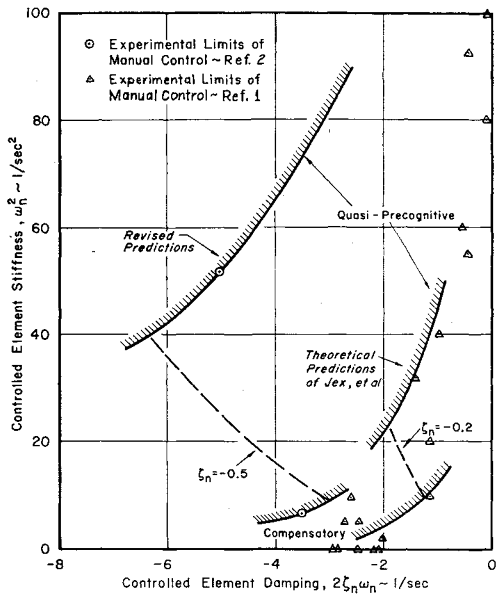

Fig. 2 Theoretical and experimental limits of manual control.

In addition, predictions of the limits of manual control made in Ref. 1 are not capable of yielding the limits of Ref. 2. In fact, as stated in Ref. 2, the experimental limits can be correlated with theory only if it is assumed that the human operator is capable of generating a second-order lead equalization. This is believed to be true, since, in the compensatory tracking case with random inputs, there appears to be no justification for assuming operator reaction time delays less than about 0.12 sec (for all of the controlled elements) or first-order lead time constants greater than about 5.0 sec. Incidentally, distribution data given in Ref. 2 supports use of the linear theory for prediction of the limits of manual control.

Interestingly enough, however, it was shown in Ref. 2 that controlled element dynamics do exist for which reaction time delays less than 0.12 sec are possible. In these cases the compensatory model of Fig. 1 is not rigorously applicable, because, after much practice, the operator adapts a more sophisticated control technique. This form of adaptation appears to be possible only for those controlled elements yielding persistent, closed loop oscillations. It is these controlled element characteristics that are labeled "quasi-precognitive" in Fig. 2.

However, as Washizu and Miyajima point out, it may be that abnormally small operator reaction time delays can occur for any oscillatory system whenever no system input is present, since, in those cases, the operator's self-adaptive behavior is not suppressed, as it is in the presence of random inputs.[4]

In conclusion, it should be apparent that the data of Ref. 1 do not represent the limits of manual control. Nevertheless, this data is valuable, because it does indicate those second-order systems, which can be controlled on a "first encounter" basis. Such information may eventually prove useful in the design of autopilots for advanced aerospace vehicles.

Received July 2, 1965.

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Reply by Authors to R. H. Smith

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THE objective of the comment by R. H. Smith seems to point out that the controllability limits as given by Refs. 1 and 2 disagree widely because of the difference of practice, and that predictions of the limits of manual control made by Ref. 1 are not capable of yielding the limits of Ref. 2. It is noted at the beginning that we shall confine subsequent discussions to second-order controlled elements with positive static stability, namely, with positive stiffness, unless otherwise stated.

Replying to the first part of the comment, we agree that practice is an essential factor for explaining the discrepancy, although it should be remembered that no system input is present in the experiment of Ref. 1, whereas random inputs are present in that of Ref. 2. As mentioned in Ref. 1, we conducted experiments for obtaining the difference between the controllability limits at one trial and at three trials and concluded that the results indicated, evidently, the effect of practicing.

The controllability limit of a human operator may depend on many factors such as practice, his naiveté, or experience as an airplane pilot, and so forth. Consequently, it is considered indispensable when presenting data on the controllability limit to prescribe conditions fully under which experiments have been conducted. We believe that our data show *a* controllability limit under the prescribed test program of Ref. 1, namely, a controllability limit at one trial and at three trials. We note that our data agree very well with those obtained by NASA in Ref. 3.

On the other hand, we find in Ref. 2 that the two controllability limits, the establishment of which required nearly 900 trial runs, show clearly the effect of heavy practice. This is *a* controllability limit established by Smith. It seems probable that a more sophisticated technique would further improve the controllability limit established by him. We note here that unpublished data obtained recently at National Aerospace Laboratory of Japan also show that the controllability limit can be improved by heavy practice far beyond that of Ref. 1.

In replying to the second part of the comment, we agree that a transfer function, which is more complicated than Eq. (3) of Ref. 1 must be employed in predicting the limits of Ref. 2. The purpose of writing Ref. 1 was this: we assumed that the transfer function of a human pilot was given by Eq. (3) and that the pilot could conduct a self-adaptive control. Then, we made a speculation to find how our prediction could correlate with our experimental data. During the prediction, we were satisfied with obtaining a rough idea of the controllability limit by taking $T_L = \infty$, although it was possible to take an assigned value for T_L. We believe that Eq. (3) is an appropriate transfer function of a human pilot who is trying to find a controllability limit on a "first-encounter basis."

Received July 30, 1965.

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A brief mention is made here on an operator's behavior under heavy practice. Since there exists a periodicity in transient response of the controlled element with positive static stability even if the response may diverge, the operator is aware of the frequency and time to double amplitude of the response during a series of the practice. There exist indications that have led us to believe that, as the practice proceeds, the operator can improve the controllability limit by taking the response characteristics into consideration and employing a second-or-more higher-order lead equalization or the so-called "quasi-precognitive" technique. Consequently, we may conclude that the operator under heavy practice is employing a more sophisticated technique than that expressed by Eq. (3).

The second-order lead equalization technique may probably be favorably employed only within some region of the static stability and damping. For example, too small or too large values of positive static stability may be unfavorable for an operator who wants to employ the improved technique. On the other hand, this technique may not be so favorably applicable to controlled elements with negative static stability as it is to those with positive static stability, since the transient response in the former is aperiodically divergent.

The authors wish to thank Smith for the comment and agree with him in stating that the effect of practice on the controllability limit of a human operator is a very important subject and in hoping that more research will be conducted to clarify its mechanics in the future.

References

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Combustion Instability in Gas Rockets

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ROCKET motors burning premixed gaseous propellants have been used by several investigators[1–3] to study the longitudinal mode of high-frequency combustion instability. The experimental results of these investigators differ in one important aspect. Zucrow and Osborn[2] and Tsuji and Takeno[3] have observed one region of unstable operation located around the stoichiometric mixture ratio. Pelmas et al.[1] have found two unstable regions, one on either side of stoichiometric.§ This apparent difference in the observations of these investigators has resulted in some uncertainty

Received July 16, 1965. Research sponsored by Air Force Office of Scientific Research, Office of Aerospace Research, U. S. Air Force, Contract No. AF49(638)-1268.

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§ An unstable region is a region in the equivalence ratio-combustion chamber length plane or equivalence ratio-combustion pressure plane where combustion pressure oscillations are observed.