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A DISCUSSION OF THE STABILITY REQUIREMENTS FOR A LAUNCH VEHICLE FLIGHT CONTROL SYSTEM

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ABSTRACT

It is asserted in this report that what is truly desired of a launch vehicle flight control system is the ability to bound the dynamic responses of the launch vehicle to winds aloft and vehicle anomalies. Within this context, the necessity of imposing the customary stability requirements on a launch vehicle flight control system is questioned. Arguments for and against the usual stability requirements are presented. It is concluded that the question is an important one which needs resolution. Comments from interested persons are solicited.

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SUMMARY

It is asserted in this report that what is truly desired of a launch vehicle flight control system is the ability to bound the dynamic responses of the launch vehicle to winds aloft and vehicle anomalies. Within this context, the necessity of imposing the customary stability requirements on a launch vehicle flight control system is questioned. Arguments for and against the usual stability requirements are presented. It is concluded that the question is an important one which needs to be resolved. Comments from interested persons are solicited.

INTRODUCTION

The author and members of the research staff at Honeywell, Inc. have recently engaged in a brief and informal discussion about whether or not one should impose the customary stability constraints on the launch vehicle flight control system. Those thus far involved in the discussion agree that what is truly desired of the launch vehicle's performance is bounded dynamic response and not asymptotic stability with respect to initial conditions. The question is whether or not stability requirements should be imposed in order to qualitatively assure bounded response. Because of the fundamental importance of the subject, the author has been requested to document the discussion to date. We hope the readers will be stimulated to consider the questions raised and to contribute to the discussion.

The reader is cautioned that so far the discussion has not been rigorous. As a matter of fact, handwaving has been the mathematical device most frequently employed. For reasons of professional pride, if for no other, the author would have preferred to have a more rigorous problem definition than can yet be provided. Nevertheless, the following thoughts are set forth. The reader is invited to comment on the matters under discussion. Written comments are preferred. Depending on progress and interest in this matter, further publications on the discussion may be forthcoming.

SECTION I. OVERVIEW OF THE PROBLEM

It is customary to impose on the launch vehicle flight control system constraints both on the dynamic performance of the vehicle-controller system and on the stability margins of the system when the system is analyzed by conventional, frozen-coefficient, linear system stability analysis techniques such as Nyquist plots.

During the operation of the first stage of a launch vehicle, the vehicle's behavior is influenced predominantly by the winds aloft. Because of the recent increase in the quality of the statistical data available concerning the winds aloft, research on the design of the launch vehicle flight control system has tended toward a statistical formulation of the problem.

A review of our current constraints has arisen because Dr. G. B. Skelton and his associates at Honeywell have been working under contract to groups within the Aero-Astrodynamics Laboratory to use optimal control theory to design a practical launch vehicle flight control system which will minimize the probability of the vehicle exceeding any dynamic constraints during first stage flight (Ref. 1). The theory uses a deterministic, linearized model of the launch vehicle with truncated modal expressions for flexure and propellant slosh. Because of the finite time of operation of the launch vehicle, the theory does not require that the resulting system be stable.

The question that has arisen is the manner in which one should handle the plant uncertainties, modeling errors, and other factors that cause the response of the actual vehicle to differ from that of the model used to construct the optimal controller. The author claimed that one should require stability margins on the performance of the vehicle controller with the given plant model in order to "assure" adequate performance with the real vehicle, even if this comprises some optimality with respect to the admittedly excellent measure of performance. This idea is developed further in Section II.

The majority of the Honeywell personnel disagreed with the author. Their argument is that since the current stability techniques are not theoretically justifiable, these techniques should not be used as a design criterion, although they are good design aids. Honeywell does admit that the current use of the theoretically sound techniques would involve an excessive amount of computational effort. Honeywell's arguments are developed in Section III.

Dr. Skelton of Honeywell pointed out that Mr. Edinger of Honeywell's Aerospace Division found that he had to trade off load-relieving performance and first stage terminal performance on his recent Saturn V/Voyager load relief study in order to meet stability constraints. Because of the absence of stability constraints, their current research effort on the same vehicle shows no such trade off and the control system achieves better performance at both times of flight.

The discussion is currently at a stalemate. The author agrees that the basic problem is one of bounded responses in the face of uncertainties and not one of stability of the deterministic model. However, there are currently no better techniques that can be applied with anywhere near as much ease as the stability constraints, which experience has shown to work. He recognizes that these techniques are theoretically not justified and that one could conceivably cause problems by the indiscriminate use of stability requirements. Honeywell personnel, in turn, recognize that their formulation, although theoretically sound, is currently not computationally feasible.

There are probably two aspects to the ultimate solution of the dilemma. The first is to develop computationally attractive techniques of assuring bounded response of the vehicle even in the presence of the model uncertainties. The second is to sell the practicing engineer on the notion of abandoning stability for the newer techniques when they become available. The immediate solution is even less obvious than the ultimate solution.

SECTION II. ARGUMENTS FOR STABILITY

Without rigorous mathematical justification, it is asserted that some form of stability with an associated measure of performance (i.e., measure of degree of stability) is required to establish confidence in the performance in the controller. For any given model of the launch vehicle's motion, all that is required in the way of performance is "adequately" bounded responses. In a statistical sense, this is assured by examining the covariances of the various states. The problems come in assuring that the actual vehicle's behavior will be "similar enough" to the behavior predicted by the model that one can have confidence in the performance of the vehicle when employing the given controller, which was designed using the given model.

The plant model customarily used in control design efforts either is or can be in error for at least four reasons.

(1) The model is linear. The launch vehicle's motion is truly nonlinear. Judicious linearization will facilitate analysis and more readily permit generalizations about the qualitative nature of the behavior in neighboring states, as long as one has confidence that neighboring states at a given time remain closely neighboring states.

(2) The model is deterministic. The physical parameters of the vehicle and, indeed, the controller itself, are only known to within certain tolerances with a certain confidence level. One would like to be assured that statistically probable variations in the plant or controller parameters will cause only small changes in the performance. This can be accomplished by root-sum-square analysis, statistical analysis (assuming linear plant and nice probability distributions, etc.) or other means. The quick and crude engineering approach used in the past has been to do classical stability analyses on the linear system with constant coefficients at various times of flight and require enough stability margins to gain confidence that the performance with small parameter variations will remain stable. One cannot justify rigorously the use of this technique, but one can appreciate its simplicity, as long as he does not become enamoured with it.

(3) Even if the model conformed to reality, we truncate the normal mode expressions for the propellant motion and the flexible structure. As long as the motion is stable, we know that the truncated modes will not significantly affect the vehicle's performance.

(4) There are some minor phenomena associated with launch vehicle motion, such as panel flutter and plume impingement, that we do not know well enough to model. They have not caused trouble in the past and should not in the future, as long as the vehicle is not operating in a critical manner. Liapunov stability about the nominal trajectory at all times gives one more assurance that the vehicle will not be operating in a critical manner at some future time for most initial conditions along the flight path.

In summary, it is asserted that one does not only want stability with respect to initial conditions or stability with respect to the probable disturbances for the given model; one also, in some sense, wants stability with respect to "neighboring plants" or "neighboring models."

In the January 1968 issue of Aeronautics and Astronautics, S. W. Golomb has a delightful article on modeling. As he phrased it, with regard to a model, "don't eat the menu." Stability does give some comfort in the face of the uncertainties concerning the model and does so at a relatively easy cost.

SECTION III. REBUTTAL

1. It was at least implicitly asserted in Section II that the application of constant coefficient, asymptotic stability criteria to controller design for a launch vehicle is reasonable if it produces satisfactory controllers.

However, the launch vehicle problem is a finite time, time-varying system problem, and the goal of control is to bound responses or, taking into account the very large winds which can occur, to minimize the likelihood of occurrence of a response which is too large. While asymptotic stability is a mathematical concept defined to conveniently treat bounded responses, asymptotic stability formally is not applicable to boosters because of the finite time of booster control. Root loci or other constant coefficient criteria are not applicable both because of the finite time and because the booster dynamics are time varying.

While stability criteria are useful design aids in any linear booster problem where one might wish to use stability criteria as measures of bounded response, one can as well use existing, fully developed covariance analyses. That is, stability is not needed since bounded response can be better measured by other methods. Furthermore, imposing stability can degrade booster performance, especially in the high dynamic pressure region of the flight and near the final time. In the latter case, stability does not allow the designer to take advantage of dead-beat control methods.

The conclusion is that stability is useful as a design aid, but it should not be a design criterion, and it is not needed as a design criterion because more appropriate criteria exist.

2. The concern over truncated modes is well founded. From experience and intuition, low-passing the control system so as to not excite ignored modes is a reasonable approach, but one <u>must</u> test models with additional modes to show that it will be successful. In a recent aircraft study, for example, the sixth symmetric flexure mode could not be ignored, and designs based on fewer than six modes failed.

3. The concern over parameter variations is also well founded. Parameter variations are usually not a problem in low gain systems, but controllers which tune out resonance peaks can produce violently divergent responses if the resonance frequencies change.

It is essential that design methods that will fly all possible parameter combinations be developed. The only theory known which accomplishes this is prohibitively cumbersome and expensive. Today, not possessing a practicable theory, the designer is forced to test all possible parameter combinations which might produce too large responses.

4. Whether or not nonlinearities must be taken into account in the design depends upon the nonlinearities. Stiction and backlash types of nonlinearities must be included in the model, but saturation types of nonlinearities and velocity product nonlinearities can usually be ignored.

Nonlinearities must be modeled, however, before any such judgments can be made. Not modeling panel flutter and plume impingement is dangerous; for example, one might mount an accelerometer where it will pick up panel flutter to the extent that the accelerometer output is fully saturated. In many cases, complete descriptions of the nonlinearities are not needed to know they can be ignored, but in every case enough must be known to rationally make this judgment. If nonlinearities which are known but ignored have not caused problems in the past, and the designer does not know why, the designer was lucky.

This summarizes the general comments on the points made in Section II. However, two detailed arguments which were made in the discussions and which support the above deserve mention also.

(1) It is known from the theory of ordinary differential equations that a sufficient condition for the stability of a system of nonlinear, autonomous differential equations is that the variational equations (linear perturbation equations) be stable. However, it is known also that the stability of variational equations does not guarantee the stability of general time-varying systems.

(2) It is known from linear optimal control theory that unstable degrees of freedom which cannot be measured cannot be stabilized, regardless of whether or not they are mathematically controllable (i.e., they would be controllable and thus stabilizable if their states would be measured). Furthermore, linear optimal controllers will always reduce or completely cancel the inputs to such degrees of freedom if the degrees of freedom appear in controlled responses. In such cases, the responses of the controlled system may appear to be completely satisfactory since the unstable states are not excited. However, small parameter variations can upset this balance and produce divergent responses.

Thus, designing controllers for nominal systems is dangerous. Usually, however, the designer is aware of traps of this type and avoids them. If he is not aware of them, he will become aware as soon as simulation tests are run. He may not be aware of them if the overall system is very complex and he is using formal design methods. The conclusion is that simulation tests of complex systems are most desirable.

One suggestion made in the course of the discussions also deserves mention, namely, the suggestion that attempting to bound the booster responses with the responses of far simpler models might be fruitful. Bounding equations of this nature are widely used in orbital mechanics, in fluid mechanics, and in a wide variety of nonlinear control problems, and it may be possible to extend these methods or develop new ones for the booster.

The bounding equations might take any one of several forms. The complete booster model is nonlinear, stochastic in its possible parameter values, and of infinite dimension in that flexure must be described by partial differential equations (PDE's). One might attempt to:

- Find a finite model (or a set of ordinary differential equations) whose responses will bound the PDE's.
- Find simple nonlinear models whose responses will bound the booster nonlinear responses.
- Find simple equations for functions which will bound the booster responses, such as Lyapunov functions expressible as solutions of ordinary linear differential equations.
- Find simple models or bounding functions which would bound all possible booster responses (parameter variations).
- Combinations of the above.

All of the above approaches have been successfully used on one or more problems in the past.

In summary, concerns about model inadequacies are well founded, and attempts to assure that the model inadequacies will not cause problems by using stability theory notions are most reasonable. Stability should not be employed as a criterion, however, because it does not fit the booster problem and because criteria which do fit the problem are available. Although a number of approaches to model inadequacy problems are suggested, none of them are sufficiently developed to be of use to booster control designers today.

CONCLUSIONS

A launch vehicle flight control system is currently required to have specified stability margins when the frozen-coefficient linear model is analyzed by conventional stability analysis techniques. The personnel so far involved in the discussion appear to agree that requiring stability for its own sake is not justified. There is disagreement as to whether or not it should be imposed for other reasons. This is an important question and needs to be resolved. If stability should be abandoned, computationally attractive alternate means of assuring satisfactory response should be developed.

The reader's participation in this continuing discussion is solicited.

REFERENCE

L. D. Edinger, et al, "Design of a Load-Relief Control System," NASA Contractor Report CR-61169, April 21, 1967.

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APPROVAL

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By

Jerome R. Redus

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense of Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This report has also been reviewed and approved for technical accuracy.

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