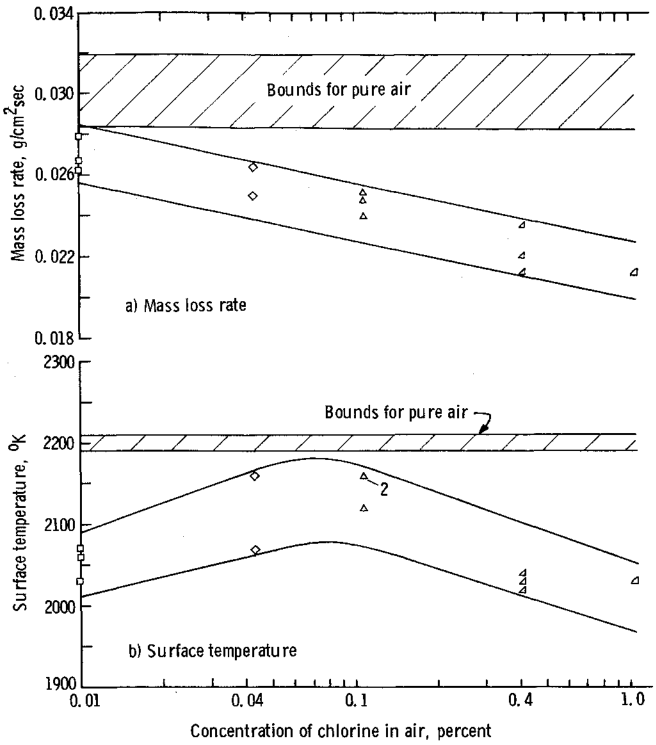

Fig. 1 Effects of chlorine addition on ablation performance.

explanation for this peculiar behavior is offered here. To put this apparent anomaly into perspective, however, attention is drawn the the similarly peculiar behavior of carbon in exhibiting a maximum in its oxidation rate curve as a function of temperature (see, for instance, Ref. 10), a common explanation for which is that there are two types of active reaction sites on the surface.[10] It is not altogether unreasonable that the present phenomenon might be somehow related.

In agreement with the previously mentioned results of other investigators, the surfaces of the graphite specimens oxidized in the presence of chlorine differ in appearance from those oxidized in pure air. They tend to be blacker, less reflective, and are thoroughly dotted with minute pits, which are likely due to selective oxidation of the surface. This latter phenomenon is probably related to the increase in BET area noted by Pallmer.[6] These differences in surface appearance are negligible at the lower chlorine concentrations but become quite noticeable at the higher concentrations.

In addition to the chlorine concentration itself, the extent to which chlorine inhibits carbon oxidation may depend on other factors such as temperature, pressure, and specific type of carbon. For example, whereas in the present study a reduction in mass loss rate of one-third was measured at a chlorine concentration of 1%, Ref. 2 experienced a reduction of as great as 79% at the same chlorine concentration, but at different reaction conditions. Moreover, because chlorine will be less strongly bound to the surface the higher the temperature, it is expected that the extent of inhibition will tend to decrease as the surface temperature increases. Hence, to establish the full potential for chlorine as an inhibitor for aerospace applications, its effect on ablation should be determined in a wide variety of dynamic environments.

Potential Applications

The methods by which the inhibiting effect of chlorine can be applied in practical situations to reduce the ablation rate of graphite or of charring ablators are several. In those situations in which forced transpiration cooling is being employed, the obvious method of application would be to add small amounts of chlorine to the injected gas. Another method of application, particular for use with graphite, would be to impregnate the pore structure of the graphite with a polymer which releases chlorine upon pyrolysis. For charring ablators, a related method would be to build chlorine or chlorine-containing groups into the polymer structure itself, which chlorine would then be released as the polymer chars. One rather fascinating method which could be used with many charring ablators takes advantage of the fact that hollow spheres of phenolic resin or glass are often added to the polymer as structural, low-density fillers. These spheres could be filled with chlorine during their fabrication, and, as the spheres ablated or melted, this chlorine would be released to inhibit char oxidation.

Conclusions

It has been shown that small amounts of chlorine gas, when present in a high-temperature, supersonic air environment, can inhibit the ablation rate of graphite and depress its surface temperature below that obtained in pure air. The extent of inhibition and temperature depression depends on chlorine concentration. In the present study at a chlorine concentration of only 1%, mass loss rate was reduced by almost one-third of that in pure air. Several methods have been suggested by which this inhibiting effect of chlorine can be applied in practical situations to reduce the ablation rate of graphite or of charring ablators.

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Feedback Control of Flutter Instability in a Continuous Elastic System

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THIS Note reports progress made since presentation of Ref. 1 at the 11th Structures, Structural Dynamics and Materials Conference in April 1970. In that paper, Moon and Dowell derived the equations for a cantilevered beam with follower force controlled by a separated sensor feedback force. A sketch

Received December 7, 1971. The author is indebted to his advisors E. H. Dowell and F. C. Moon for their continuing support and guidance.

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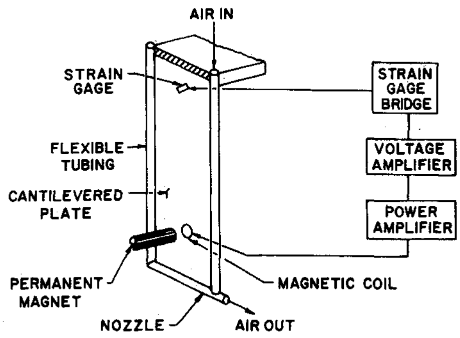

Fig. 1 Schematic of system.

of the beam is shown in Fig. 1. The air jet mounted on the bottom of this beam provides the body fixed follower force which leads to a "flutter" type instability above a critical value of jet velocity or jet force.

The object of the research is to increase the jet force at which the beam flutters by applying a force on the beam proportional to bending and/or torsional strain. The elements of the feedback system are also shown in Fig. 1. The signal from the semiconductor strain gauge is amplified by signal and power amplifiers and then led through magnetic coils mounted on the beam. The magnetic fields of these coils interact with those of permanent, stationary magnets mounted off the beam to provide the control force.

Although analytical studies of the effect of various means of feedback compensation have been made, the system reported here employs no compensation other than amplitude gain. Furthermore, phase shift in the feedback loop has been measured and found to be small. Consequently it has been ignored in the analysis.

Since the publication of Ref. 1, a new test rig was built which allows greater precision and flexibility in the application of the control. The results reported here are from tests in which the location of the control force on the beam is varied.

Figure 2 shows the experimental and theoretical stability boundaries for the control system which senses torsional strain at the root and applies a proportional force at 0.9 length of the beam from the root. λ is the nondimensional jet force and λ_c is the nondimensional control force (lb force/unit strain). See Ref. 1 for notation. $\lambda_c < 0$ indicates stabilizing feedback. Shown along with the experimental curve are analytical curves using five and three natural modes (three bending, two torsion and two bending, one torsion, respectively).

The experiment and the five mode analytical boundaries are composed of two different types of instabilities: a flutter and a divergence. For small $|\lambda_c|$ the first torsion mode is stiffened, resulting in a slower rate of convergence of the first two bending mode frequencies. This means that a greater jet force is required before these two modes converge and break away

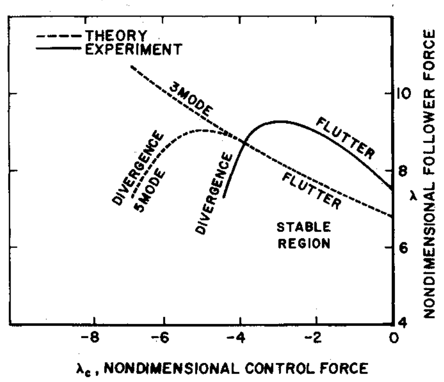

Fig. 2 λ **vs** λ_c **for** $Z_c = 0.9$.

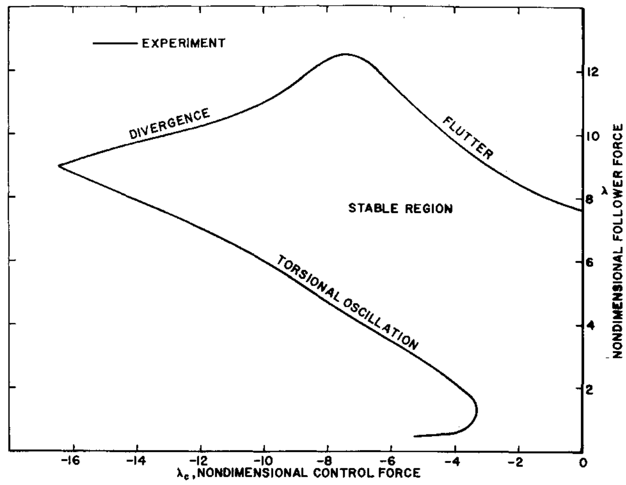

Fig. 3 λ **vs** λ_c **for** $Z_c = 0.3$.

from the imaginary axis loading to a "flutter" type instability. If only three modes were involved, the first torsion mode would always be stiffened by increasing control force and an ever increasing jet force before flutter would be experienced. However, the presence of higher modes eventually reverses this tendency of the first torsion mode to the extent that one mode is eventually driven down to the real axis and divergence at decreasing jet forces for increasing control force is experienced.

Before the divergence instability dominates the boundary, an experimental increase of 28% in jet force required to flutter is achieved. There is good agreement between the experiment and the five mode analytical model. This model, however, employs only diagonal mass and stiffness matrices ignoring any coupling of the pure beam modes due to coil or air jet mass and stiffness. It is remarkable that a model this simple will predict the beam behavior as accurately as it does.

This simple beam model predicts that the greatest improvement in flutter force will be achieved by locating the control force in the lower half of the beam. The exact location is very dependent on an accurate natural frequency determination of each mode. However, in Fig. 3, results are shown obtained with a control system identical to the one just described, but with the control placed at 0.3 of the length of the beam from the root. An increase of flutter force of 65% is achieved along with a much more complicated stability boundary. In addition to the types of boundary already described, a third segment which turns the curve back towards the λ axis appears. At this boundary, a torsional oscillation occurs at the first torsion frequency. This simple model used to predict the behavior with the control at 0.9L fails to indicate any increase in flutter force at 0.3L. Efforts are now under way to improve the analytical model to enable it to predict this stability curve.

Other related studies are cited in Ref. 1. In addition, Ref. 2 describes an electromechanical analog of an autopilot and elastic missile which simulates the coupling between the aerolastic body and the autopilot.

Conclusions

Experimental increases of force before flutter of 28–65% have been achieved with a simple feedback control. Presently available theory is adequate to predict the results of the smaller but not the larger increase in flutter force due to feedback.

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