tests the stall was limited to a few intermittent stall cells of small amplitude.

The tests of the rotating stall control system on the J-85-5 engine were performed to demonstrate the performance of the control system on an operational compressor. The tests were performed under sea level static conditions, both with and without inlet distortion. On the engine, the stall control was installed to override the normal operating schedule of the compressor bleed doors and inlet guide vanes. The J-85 was stalled in two ways, first by closing the bleed doors at constant engine speed, and second by decelerating the engine with the bleed doors partially closed at the beginning of the deceleration. A total of 41 compressor stalls were recorded at corrected engine speeds between 48 and 72 percent of the rated speed. All of the rotating stalls which were induced on the engine were cleared rapidly by the control system without damage or flameout in the engine. The duration of the stalls which did occur were limited to 325 milliseconds or less. Thus, it is concluded that the tests were successful in demonstrating that the control is capable of detecting and eliminating rotating stall in an operational jet engine. The tests did suggest that the manner in which the stall control system is incorporated into the engine control system could be improved. Such improvements are being made at the present time and further stall control tests on the J-85 engine will be performed.

Acknowledgments

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DISCUSSION

S. E. Arnett[2]

Compressor stall problems related to turbojet engines were born with the engines, and the problems became more severe with the transition from centrifugal compressors to axial flow compressors. The necessity of avoiding stall combined with a need for rapid engine acceleration has been a major factor in turbojet engine control requirements. The Bendix Corporation and specifically Energy Controls Division have been associated with the design and manufacture of turbojet engine controls since the end of World War II. In conjunction with the turbojet control activity, Bendix was funded by the Navy in the early 1950's to investigate engine stall and potential technique for stall "anticipation." The work done during the Bendix program was classified and, therefore, not generally disseminated. The program was not carried to a point of hardware implementation, to demonstrate prevention or recovery from stalls. Several parameters were investigated and rotating stall was one of the parameters investigated. Tests were conducted on a J-47 engine.

The point of interest is that the noise signature of rotating stall appears to be substantially the same for the compressors investigated during the recent Calspan work and the classified Bendix tests.

The major points of departure the writer has with the subject report are in those areas of the report and conclusion where it is implied that a general solution to the detection and elimination has been obtained. The cautions that should be considered include:

- Both the J-47 and J-85 are low in terms of compressor pressure ratio obtained.

This is emphasized where the compressor characteristics are compared to current engines and variable flow engines in development.

- Observation has shown that the J-85 has a "soft" stall on acceleration.

Some experimentation with the engine was required to define techniques for producing an engine stall and the results were not violent. The J-85 is more stall resistant than any other engine encountered during our control experience.

- The methods of inducing stall covered in the report are certainly valid, but probably allow more time for detection and recovery than would be available in higher compressor pressure ratio engines.

Any requirement to move engine geometries very rapidly proves to be not practical when the hardware is sized and the actuating power and fluid provided.

- Any general approach which has a potential for being applicable to all engines would have to control (reduce on acceleration) fuel flows.

Geometry control may also be necessary but to meet many engine requirements will not be fast enough. Also, geometries are limited by physical and aerodynamic bounds on the range of effectiveness.

In summary, we feel the report represents an excellent program. However, it is believed that the "stall" phenomenon is complex, and a more sophisticated control approach will be evolved prior to anything near a generalized solution to detection and stall elimination/recovery.

R. S. Mazzawy[3] and E. M. Greitzer[4]

The authors are to be commended for their paper which is on a topic of current interest. The onset of rotating stall indeed does often limit the operating range of gas turbine engines. We feel, however, that it is useful to place their work in perspective with respect to phenomena that are actually observed during flow instabilities in aircraft engines. As such our comments are directed at two different aspects of the overall problem: 1) the attempt to prevent the initial development of rotating stall, i.e., to prevent instability, and 2) the ability to recover the system once the fully developed rotating stall flow regime is established.

Let us consider the first of these. It should be noted that the authors' experiments were limited to relatively low rotational speeds in both the annular cascade and the J-85 engine. However, the time scale associated with the development of rotating stall appears to be

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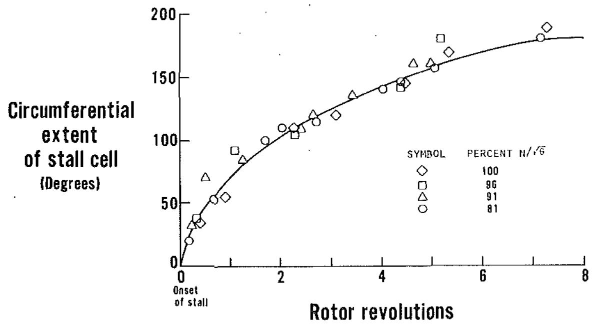

Fig. 12 . Circumferential growth of stalled region

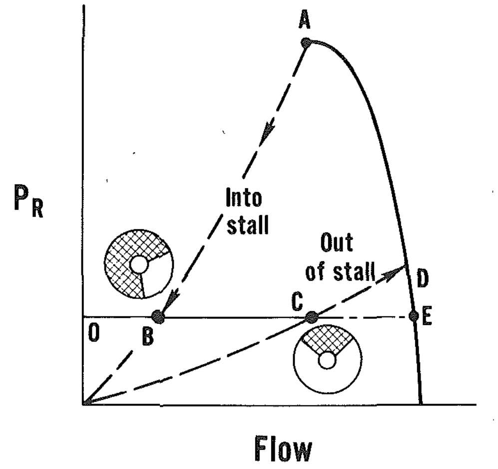

Fig. 13 Large hysteresis in stall/unstall phenomenon

dependent upon the rotor speed as illustrated in Fig. 12. The data in this figure, which is from a three-stage compressor, show the growth of a stall cell as a function of time for different rotor speeds. It can be seen that the growth of the cell appears to scale directly with rotor speed. The task of preventing rotating stall thus becomes much more difficult at high speed because of the shorter times for growth of the stall cells.

A more serious comment is that rotating stall very often precipitates an engine *surge.* In such cases it is not unusual for the surge to occur in a time of approximately one to two rotor revolutions from the initiation of rotating stall. In a modern gas turbine engine this is on the order of from *five to ten milliseconds.* Such a situation, which is the more common one at high power, was clearly not covered by the authors' experiments.

The second area on which we wish to comment concerns the ability to recover an engine from the condition of rotating stall. It is well known that a large hysteresis exists in the stall/unstall phenomenon for a multistage compressor. A sketch of this situation is shown in Fig. 13, and ample documentation of this is provided in [4] (especially the subsequent discussion by J. Harmon which shows data from 22 different multistage compressors). It can be seen that the throttle line (or operating line) must be greatly lowered in order to recover from stall, and, in an engine, this may be very difficult if not impossible to do. The problem is especially acute at high rotor speeds and, in fact, the authors noted this difficulty at the highest speed tested on the J-85 (at 72 percent of design). In other words, the difficulty of recovery increases greatly with speed, and procedures that are effective at low speed may not be at all adequate at high speed.

Thus, while we regard this effort as a start on a difficult problem, it does not seem as if the goal can be attained without:

1 substantially improving the response time of engine actuation control mechanisms, and,

2 *more strongly emphasizing the improvement of recoverability* procedures at higher speeds.

Additional References

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Authors' Closure

The authors wish to thank Mr. Arnett, Mr. Mazzawy and Professor Greitzer for their discussions of our paper. Both discussions point out that the stall control tests on the J-85 engine were performed under conditions which were not as severe as might be found in modern compressors operating near their design speeds. The authors agree that the test results described in the paper do not demonstrate that rotating stall can be controlled at high engine speeds and high pressure ratios. The test results on the J-85 engine were a first step at controlling rotating stall on an operational engine. It is worth noting that the design speed of the J-85 engine is quite high (16,560 rpm) so that the control tests at 70 percent of this value (≈11,600 rpm) are representative of larger modern compressors in terms of the time available for appropriate control action. However, the compressor pressure ratio on the J-85 at 70 percent of design speed is definitely too low to be representative of modern compressors. Nevertheless the test results did show that rotating stall can be controlled at least at moderate compressor pressure ratios and that the stall detection system was successful.

The desirability of improving the response time of the control system was pointed out in the authors' discussion of Fig. 11. Such an improvement was accomplished in some work which we have just completed. In this work, the installation of the rotating stall control on the J-85 was modifed so as to decrease the response time of the compressor variable geometry by a factor of ten. The performance of the new control installation was tested using techniques similar to those described in the paper, but the engine speed range for the tests was increased to 80 percent of design speed. The new test program had two objectives. The first was to investigate how much improvement in performance can be obtained by substantially decreasing the response time of the variable geometry on the J-85. The second objective was to determine if rotating stall can be anticipated and eliminated by proper selection of the conditioning parameters for the reference pressure, $\Delta P_{\rm REF}$ (Fig. 3).

The results from the new tests will be reported in the near future. However, it seems appropriate to mention here what we believe to be the most important result. It was found that rotating stall can be anticipated and eliminated completely at engine speeds between 65 and 80 percent of design. This was accomplished by selecting a conditioned reference pressure, P_R in Fig. 3, which was lower than that used in the original tests. With the lower reference, the control held the bleed doors open far enough to prevent stall inception for the above range of engine speeds. At lower speeds, it was possible to stall the compressor but the amplitude and duration of the stalls were very small and had no noticeable effect on the engine. Moreover the new reference level did not affect normal operation of the engine.

As noted in the main body of the paper, the configuration of the J-85 engine limited the test program to engine speeds at or below 80 percent of design speed and hence to relatively low pressure ratios in terms of modern compressors. Thus, the comments by Mazzawy and Greitzer regarding the difficulty of stall recovery at high power are still applicable to the new test results. In fact, the authors are in agreement with these comments provided that rotating stall inception is allowed to occur. However, the results of the latest stall anticipation tests on the J-85 lead us to believe that the control could be applied successfully to modern engines.