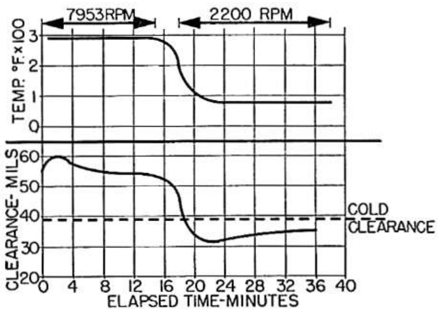

Fig. 11 Graph Showing Effect of Rapid Deceleration on Tip Clearances

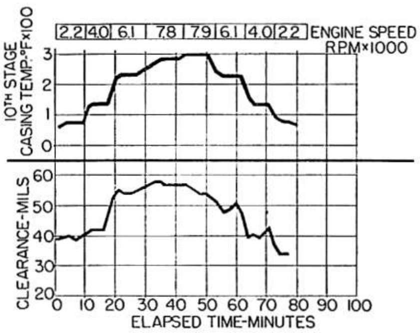

Fig. 12 Graph Showing Casing Temperature and Tip Clearances Versus Time and Speed

As in most instruments, there are limitations and precautions in their use and this instrument is no exception. Some of the precautions in the use of this instrument are obvious and others have been acquired through experience. The time of reading is one factor which should be taken into consideration when installing this instrument. As the travel is only 0.250 ipm, the closer the starting position of the probe is to the blade tips the shorter the time cycle of measurement. The flag is the limiting factor in setting this distance as it is approximately $^1/_{16}$ in. thick; thus the minimum travel which could be established is this $^1/_{16}$ in. plus the clearance of the blade tips. As the probe must travel in and out this $^1/_{16}$ in. plus clearance, the minimum reading time can be computed. The instrument constant must be known within the accuracy of measurement desired and the installation constant must be determined before the readings are of any value. The determination of these constants was discussed previously.

Another consideration which should be noted is that the mounting of the instrument should not bind the adapter in any manner as this may cause the flag to bind and give false readings or cause damage to the instrument.

Results From Use of This Instrument

The determination of operating clearances has enabled the design engineer to control the compressor clearances accurately by controlling factors which affect the clearances of an axial-flow compressor. Thus more efficient axial-flow compressors can be made by reducing the tip clearances under all operating conditions and still maintain some clearance to avoid rubbing.

The advantage of knowing the clearance of any axial-flow compressor under all conditions of operation is not yet a reality because the instrument in its present form is not readily adapted to flight testing owing to the power requirements and the auxiliary equipment required to operate the instrument.

This disadvantage of weight and power for flight-test information will be overcome in the future by a simpler system for measuring clearances. However, for accuracy and simplicity in test-cell operation this instrument does the work required, and the data which have been accumulated in numerous tests have proved the value of such an instrument.

Discussion

B. R. Anderson.[3] It is important that rotor-blade tip clearances can be measured so that the compressor may be operated at minimum clearance insuring maximum efficiency without the possibility of rubbing. The clearanceometer described in this paper has measured these clearances satisfactorily and has proved itself in giving important and useful information to design engineers.

This instrument has several advantages over other systems. The simplicity of both the mechanical head and control circuit makes it a practical instrument to use. This is an important feature when it is necessary for nontechnical personnel to operate and service the instrument. The simplicity of the unit likewise leads to a rugged and durable instrument. Because of this the mechanical head can easily withstand the vibration and other severe operating conditions. The accuracy of the readings is excellent, giving errors of only ±0.001 in. However, as the authors point out, reference measurements first must be made between the reference flag and blade tip. Then, since the control circuit contains no amplifiers, no calibration is necessary. Only the speed of the probe need be known, and this is always constant.

As for disadvantages, the first is the seemingly long time one must wait for readings. This is due to the fact that the probe travel is only $^1/_4$ in. per min. Therefore, if the tip clearance is, say, 0.1 in., the total time between readings is at least

$$2/1/4 \times (\text{tip clearance} + \text{flag thickness}) = 8\,(0.1 + 0.062) = 1\,^1/_3 \text{ min.}$$

This assumes that the inside face of the flag is exactly flush with the inside surface of the compressor casing and that the flag is dropped immediately in front of the probe when the probe is retracted far enough. This long length of time may not necessarily be a disadvantage if the changes in clearance are slow. This is not usually the case though if an engine is started cold and immediately brought up to full speed. Therefore the best application for this type clearanceometer would be for measuring clearances under stabilized conditions, or clearance versus time measurements when the time involved is 10 min. or greater. Another disadvantage is that the instrument cannot measure turbine-bucket clearances because of the high gas temperatures.

The clearanceometer is a useful and practical instrument. Any other instrument which could be built to give continuous indications or more accurate readings probably would be so complicated in design and costly to build as well as difficult to use and maintain, that its general usefulness would not be as great as the probe-type clearanceometer.

S. M. Cohen.[4] Although the paper presents the clearanceometer as used to measure the tip clearance of axial flow compressors, its application can be more widespread than this one function. However, used as presented, the device is of great value to the design and development of the gas-turbine engine by providing a means of obtaining accurate information from an engine under actual operating conditions.

The authors not only state their understanding of the appli-

[3] Electro-Mechanical Unit, Lockland Plant Laboratory, Aircraft Gas Turbine Division, Cincinnati, Ohio.

[4] Curtiss-Wright Corporation, Wright Aeronautical Division, Wood-Ridge, N. J.

cation of the clearanceometer, but offer modifications in design that will improve the over-all utility of the instrument. Their suggestion that a revision in the control circuit be made to make possible a greater number of readings per unit of time by cycling the movement of the probe from a known secondary position would eliminate the disadvantage of the probe speed. This also would allow the mechanical head to be mounted further from the position of actual measurement. Direct readings may not be possible with an oscillating probe, but oscillographs or similar recorders could be used to measure more transient conditions of engine operation than are now possible.

If minimum clearance or casing distortions are to be investigated, the clearanceometer is unwieldy by nature of its fixed position. Of course, several heads mounted in the same lateral plane could be used to indicate the amount and location of minimum clearance, the distortion of the mounting shell, and the concentricity of the rotor.

This paper demonstrates effectively that temperature and rotor speed are the prime factors in changes in compressor-tip clearances. Since these effects are equally important in the turbines that drive the compressors, an investigation of turbine clearances would yield valuable information. Here the factors of circumferential temperature distribution and, perhaps, cooling air flow with the resulting shroud or housing distortions are introduced that need evaluation at all operating conditions of the engine. If turbine temperatures are too severe for the mechanical and electrical mechanisms of the measuring head, cooling modifications could be made to accommodate the requirements of turbine clearance measurements. Another interesting possibility mentioned for use of this clearance-measuring device is the application to a flight test engine. Investigation made under flight maneuvers with an oscillating probe would be of unquestionable value. The clearanceometer is a cleverly conceived and developed electromechanical instrument that accomplishes valuable measurements not before readily obtained. The possibilities in its future development will mean an increase in the scope of information available for analysis.

Authors' Closure

We would like to thank Messers. Anderson and Cohen for their interest in commenting on this paper.

The disadvantage of time of reading as pointed out by Mr. Anderson is not as critical as might be supposed for gas-turbine compressors. The curves in Fig. 11 indicate that there is a period of approximately 5 min in which the clearance is changing from maximum to minimum for a rapid shutdown which would give the maximum change in clearances. By having the flag of the clearanceometer mounted flush with the inside of the casing, clearance readings up to 0.060 in. may be taken in 1 min, giving a possibility of taking five readings over the entire time of change. With such slow changes taking place it is only necessary to mount the clearanceometer properly to achieve the desired results.

The desirability of measuring turbine-bucket tip clearances has been considered in the design of the instrument and provisions have been made for air cooling the adapter. In the only attempt known to the authors to use this instrument for measuring turbine clearances, the probe was extended too far and no cooling air was used which resulted in a jam, caused either by the hot gases or contact with the bucket, and the probe was bent so that it could not be withdrawn. Further attempts will be made to obtain this measurement with this clearanceometer by the application of improved techniques.

As pointed out by Mr. Cohen, the determination of the minimum clearance point is difficult. To scan the clearance properly it would be necessary to have the gage rotate with the wheel. Since no gage has been proposed which will do this, it is necessary, at least for the present, to measure as many points around the circumference as possible. From these readings the minimum clearance may be estimated which is much better than no measurement at all. The problems encountered in flight-testing measurements with this clearanceometer have not been solved satisfactorily. The power supply on planes is not satisfactory for the present design. Also, the psychological effect on the pilots of a probe moving in on blades has to be overcome. A new principle is now being investigated for flight-test use which will overcome these objections.

The possibility of using the oscillating probe has not been attempted as yet, but if it is used, it will only be necessary to record the maximum reading of the counter for each oscillation as it would be synchronized with the motion of the probe until the probe was brought back to the reference.