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IMPROVEMENTS IN ROTOR PERFORMANCE BY ROTOR TIP BLOWING

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1. Introduction

Improvements in rotor lift efficiency is a subject for continuous research. The techniques which have been employed have ranged from complicated mechanical devices fitted to the blades through various mechanical tip shapes to air injection at the tip of the rotor blades.

This paper discusses a pneumatic tip device and reports interim measurements.

2. Historical Introduction

In 1967 work was in progress at the National Gas Turbine Establishment on the circulation controlled rotors which basically used high lift coefficients with small blade area and lower speeds than are used on conventional helicopter rotors. Results obtained on these rotors indicated that the induced power contribution was much larger than simple theory indicated. Wind tunnel tests with a section of a rotor blade protruding into the working section from a side wall and terminating at about mid-span indicated that tip jet propulsion units mounted at the end of the blade had a beneficial effect on the lift by moving the tip vortex outwards. At no time did the tip vortex become coaxial with the jet flow. A mechanical end plate fitted in place of the tip nozzle indicated a similar beneficial effect on the blade performance but the mechanical difficulties of mounting these large end plates on a rotating blade were considered too great to be practical. The disadvantages of having these end plates in position with the rotor in forward motion was also unattractive. The idea of using a jet sheet in place of the mechanical end plate was suggested on the basis of Stratford's mechanical flap analogy for the jet flap. Experiments were conducted by Dean, G.W. and reported in reference 1 from which Figure 1 is taken. This result includes a power allowance for the compression of the air which is sent to the tip fence. It can be seen that the best result represented a 10% reduction in power for a given rotor thrust generation.

While this result was important for rotors with high thrust coefficients it was necessary to examine the idea for blades with more normal profiles and performance factors. This is being done using the apparatus described below.

3. Experimental Rotor Rig

The University has a rotor rig which is designed for hover speed experiments. This rotor (shown in Figure 2) has an overall diameter of 9 feet (2.74m) and can be fitted with a variety of rotor heads and blades.

The rotor is driven by a variable speed electric motor which has a maximum power output of 11KW. The drive from the motor to the rotor head is by shaft through a thrust bearing which allows the shaft to move axially by about 4mm., thus allowing rotor thrust to be measured by a 'strain' gauge balance mounted just below the rotor head. This balance consists of four perpendicular strain gauged flexures which are attached between a plate that is fitted to the shaft via a deep ball bearing and the grounded rotor tower. The system is arranged so that increment can be either positive or negative relative to datum thus permitting positive and negative lift to be measured. The strain gauge balance was calibrated by connecting a spring balance between an overhead crane and the top of the rotor head via a free swivel joint. Vertical loads were applied by means of the crane while the rotor was rotated slowly below in order to ensure that there was no stiction in the system. The calibration of the system shown in Figure 3 indicates acceptable characteristics.

In order to supply the ends of the rotor blades with compressed air which could be ejected in various directions it was necessary to couple the rotor hub to the house air mains by a rotating seal and to produce rotor blades which had sufficient internal area to allow the mass flow to be passed to the tip.

Air from the house compressors was fed via a valve system to a pipe which was situated vertically above the rotor hub. Figure 4 shows the design of the air reservoir. It can be seen that air enters downwards along the vertical pipe, it emerges into the rotating reservoir via 4 slots. Air is then distributed from the sides of the chamber through flexible pipes to each of the three blades as can be seen in Figure 2. In order to keep the air blockage to an acceptable value two pipes were used from the reservoir to each blade. Losses in this air chamber were negligibly small.

The blades were constructed using a hollow D section for the nose and building up a balsa wood trailing edge as is shown in Figure 5. The blade profile is symmetrical and has a 12% thickness chord ratio.

The ends of the blades were constructed so that a plate with the blade cross section could be attached in order that the air passing along the blade emerged as a sheet sensibly normal to the chord, Fig.6. This end plate could be fitted at varying distances from the blade so varying the width of the slot. In addition different blanks could be inserted in order to arrange for the air to emerge at different positions around the profile.

4. Calibration of the Air Blowing System

An air mass flow meter (Rotameter) was mounted in the supply line to record the air volume flow to the rotor head.

The effect of the static pressure of the air fed to the blades on the lift measurements made on the strain gauge balance was examined. It is apparent from Figure 4 that there will be a pressure on the base of the housing which will not be compensated due to opening of the air inlet. Similarly the pipes going from the reservoir to the blades (Fig.2) start horizontally but end vertically - there will therefore be a vertical downward reaction force. This force has been measured and good agreement with sample estimates obtained. However it was possible to eliminate this effect in experiments by adjusting the flow to the required values with rotor turning at a slow speed, zeroing the strain gauge bridge and then recording the lift directly as the rotor speed was increased to the test speed.

5. Allowance for Compression Power

In order to make a fair comparison between a rotor with and without pneumatic tip forces the energy used to compress the air must be included in the power balance. The particular system used in these experiments was dictated by the model rig available. It does not represent the losses that would be incurred if a new rotor was designed to incorporate pneumatic fences from the outset. Nevertheless the performance given here has assumed the losses incurred in this rig and the compressor power has been calculated to provide the line total pressure upstream of the rotating seal and mass flow with the assumption that compressor has an adiabatic efficiency of 80%.

6. Experimental Results

The rotor was first run with the tip gaps sealed and with the air supply turned off. Measurements were made with the collective pitch set at 0°, 6°, 9° and 12°. Thrust was measured on the strain gauge balance and power on the electrical input to the motor. It was appreciated that this included losses within the motor but since the experiments were comparative this effect was not considered to be important. These results are shown in Figures 7, 8 and 9 and are labelled regular blades. Strip theory calculations indicate that the performance is normal.

The rotor was then run at the various pitch settings with the following slot configurations. The upper surface open from the trailing edge for 40% of the chord, Fig.7, the same slot extended to 60% of the chord, Fig.8 and finally the 60% rear upper slot together with 40% of the lower surface starting from the nose and extending rearwards, Fig.9. Various volume air flows were used and these are shown in the figures in cc/sec. Each figure shows results at 400 and 500 revs/min. The power results have all been corrected to include the estimated compressor power calculated as mentioned earlier.

The two upper slot configurations shown in Figures 7 and 8 indicate similar improvements. It is clear that additional thrust is being generated with virtually no increase in power. From the curves it may be shown that for a $C_T = 0.009$ the power is reduced by 25 to 30%. Alternatively at the same power setting say $C_p = 0.003$ the thrust is increased by 13-16%.

The third configuration with upper and lower blowing shown in Figure 9 shows no such gain. In fact with the higher volume flows it is seen that the performance becomes significantly worse than with regular blade. This result was a surprise initially until it was noted in water channel 3-dimensional model tests that blowing in the vicinity of the front stagnation point ruins the lift distribution of the adjacent section. This would appear to be happening in this case.

In order to gain information on the spanwise lift distribution a rake of 12 pitot tubes was set up 0.11 rotor radius below the rotor as can be seen in Figure 2. The pitot tubes were spaced at equal radial distance, the inboard one being at 64% of the rotor ratios and the outboard one beneath the tip. The downwash distributions are shown in Figures 10 and 11 for the 40% and 40/60% slot configurations. Fig.10 shows that compared to the regular blade the downwash has increased near to the tip and the outboard limit of the downwash has moved outboard. Integrating these results shows a similar increase in lift to that obtained from the strain gauge balance. Some smoke pictures obtained for similar conditions are shown in Figure 12. These photographs were obtained using a trigger from the rotor shaft so the flow development in each case is at the same stage of development. The change in flow pattern shows a similar change to that indicated by the downwash rakes.

The results for the 40/60% slot model show a different picture with the tip flow apparently being less well developed and the downwash not extending outward as shown in Figure 10. This result would appear to be compatible with the hypothesis that the lift has broken down on the outer blade section probably due to blowing near to the front stagnation point.

7. Conclusions

Preliminary experimental results have indicated that blowing air normal to the chord of the blade at the tip can produce significant increases in thrust (13-16%) at the same power or alternatively 25% reduction in power for the same thrust.

This result appears to be achieved by increasing the lift on the tip section and with corresponding improvements in the lift distribution inboard. This effect is compatible with a tip fence or tip shroud performance.

Blowing near to the front stagnation point can however produce adverse effects.

The fact that similar gains were produced on the heavily loaded blades of the circulation rotor fitted with a totally different blade section indicates that the effect is not peculiar to any one rotor configuration.

Further work is being performed to assist in understanding and optimising this mechanism.

8. Reference

1) G.W. Dean, Some Experiments Concerning the Tip Drag of a Circulation Controlled Cylindrical Lifting Surface with and Without Tip Fences. National Gas Turbine Establishment 1969. Unpublished.

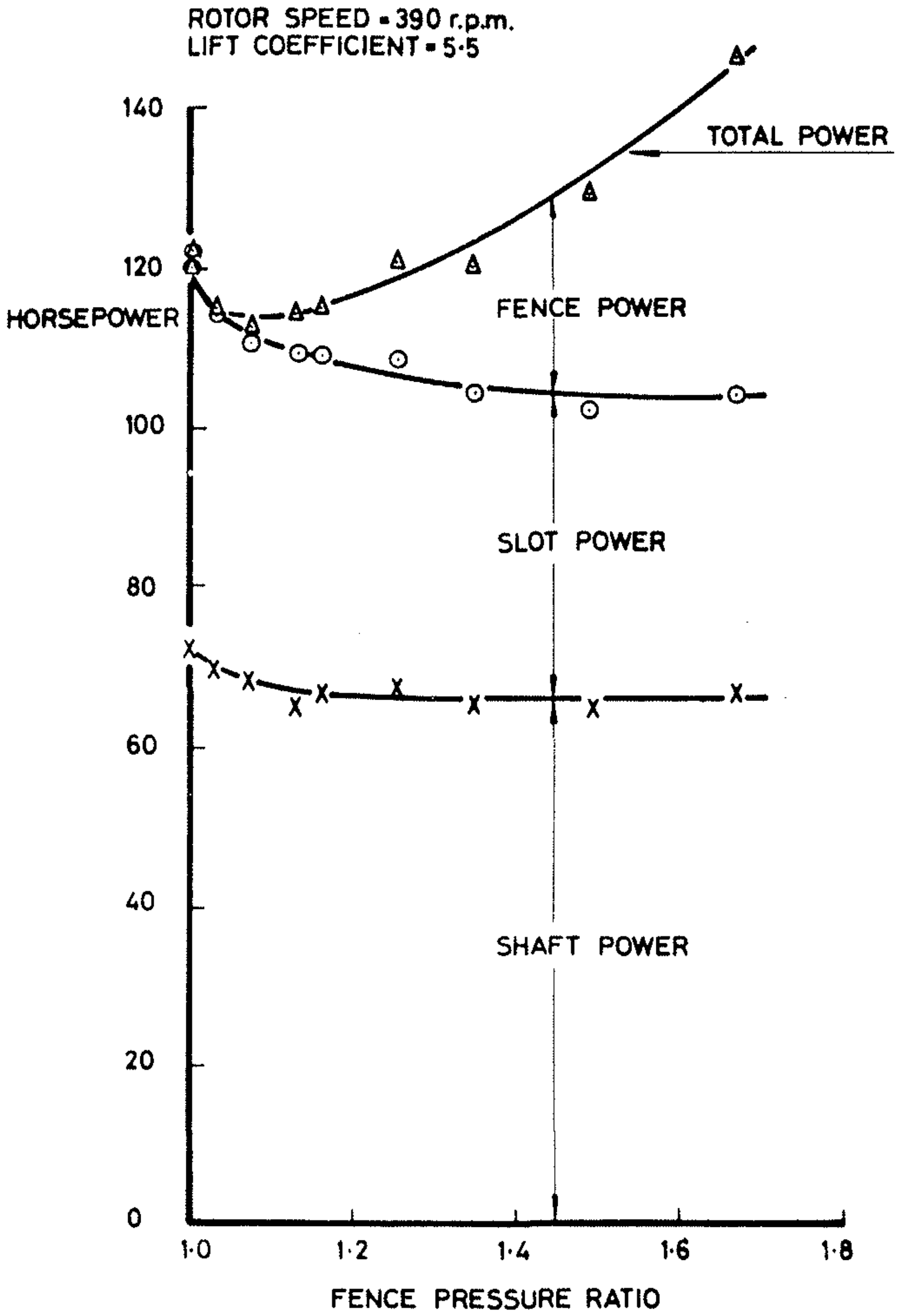

FIG.1 EXPERIMENTAL ROTOR TEST WITH PNEUMATIC TIP FENCE.1

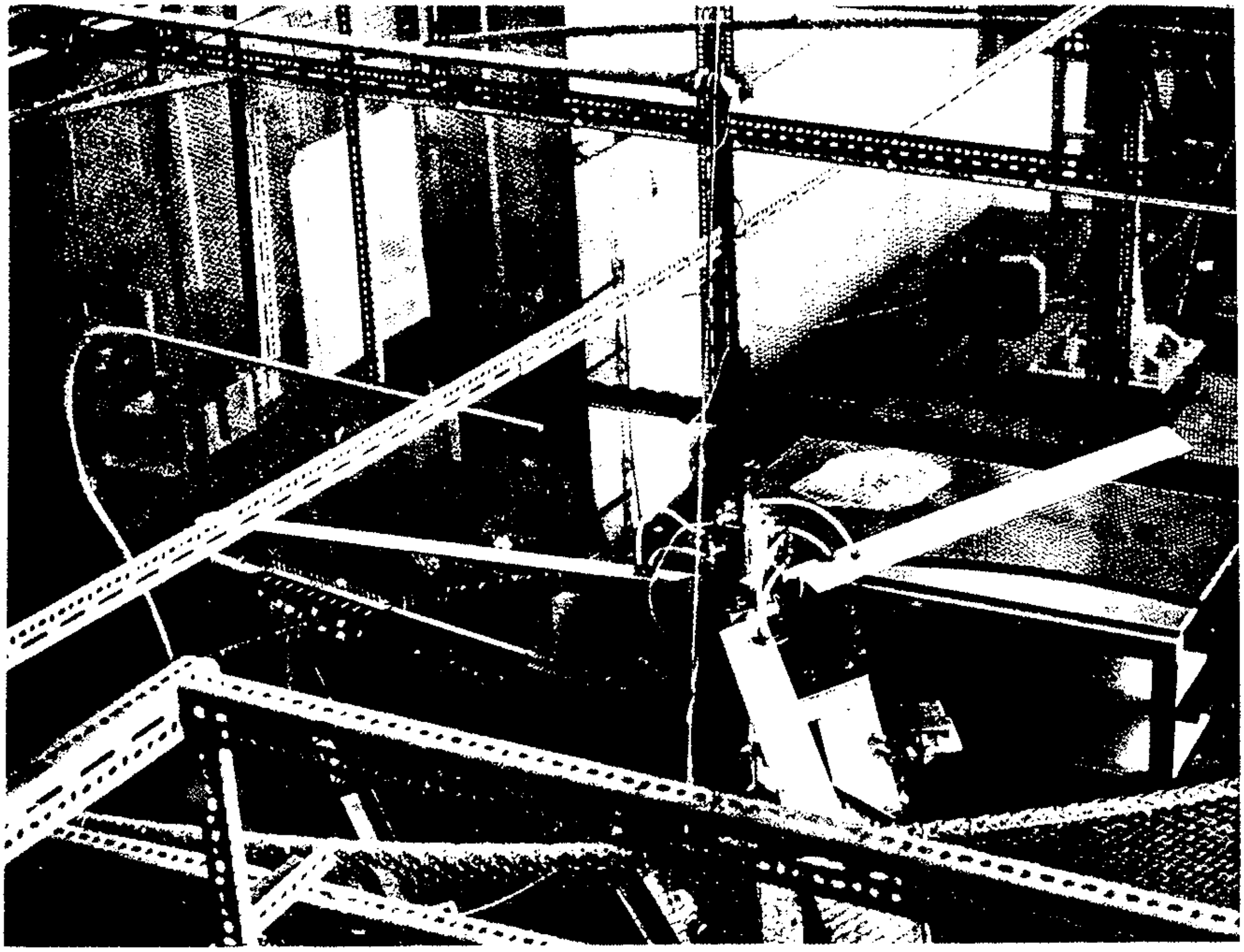

FIG.2 HOVERING ROTOR RIG

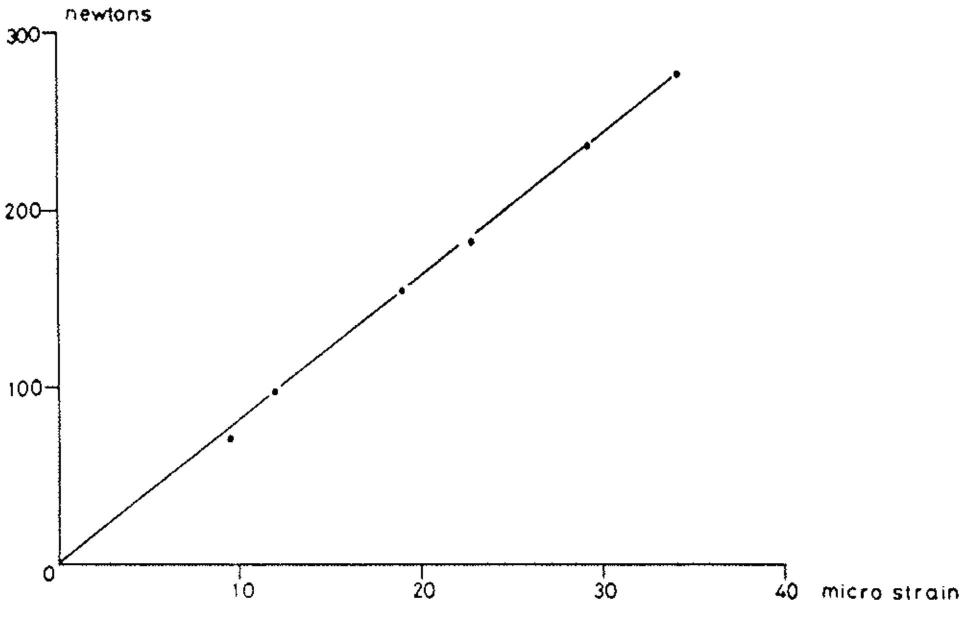

FIG.3 STRAIN GAUGE BALANCE CALIBRATION

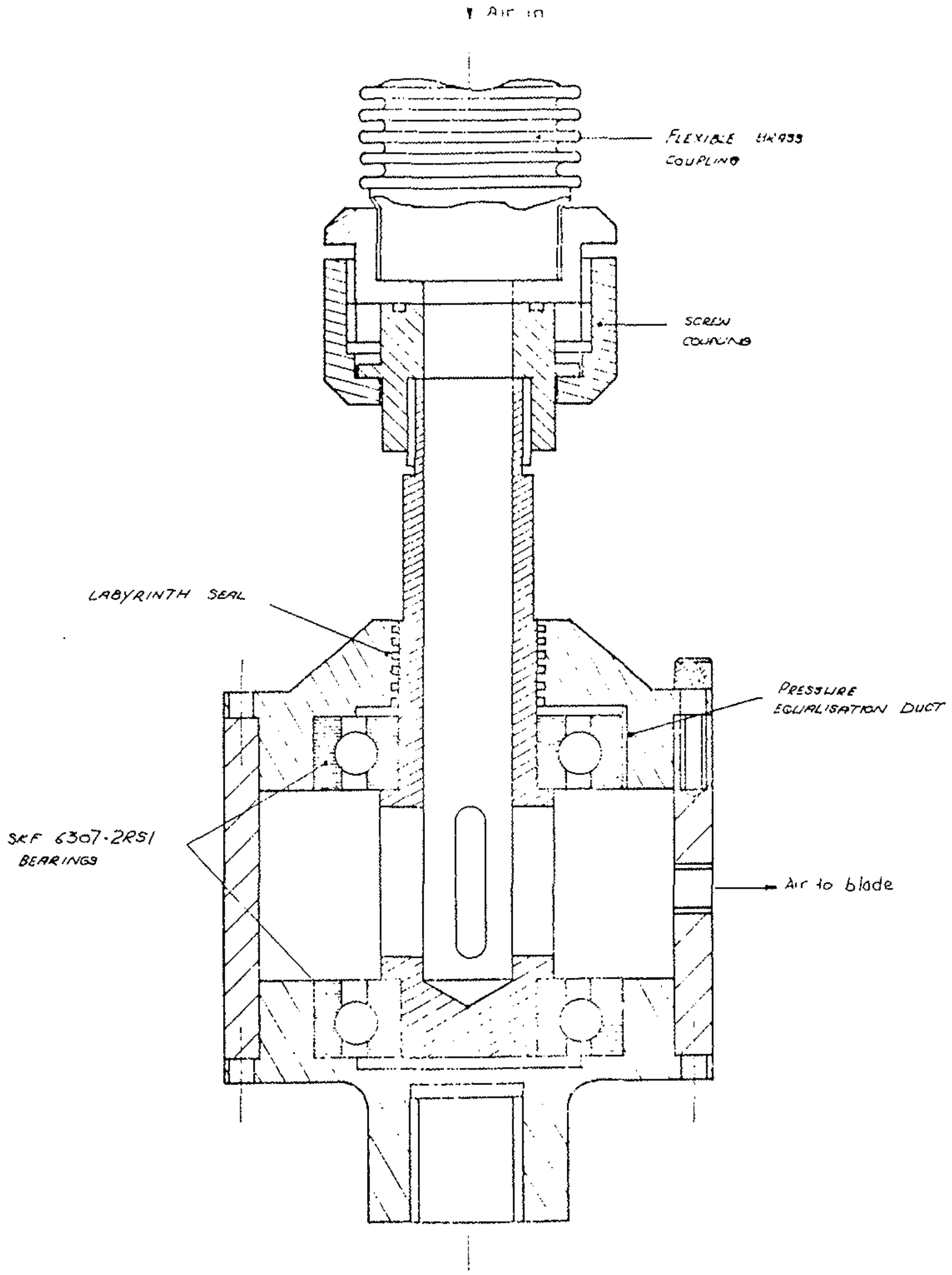

FIG.4 ROTATING AIR HOUSE

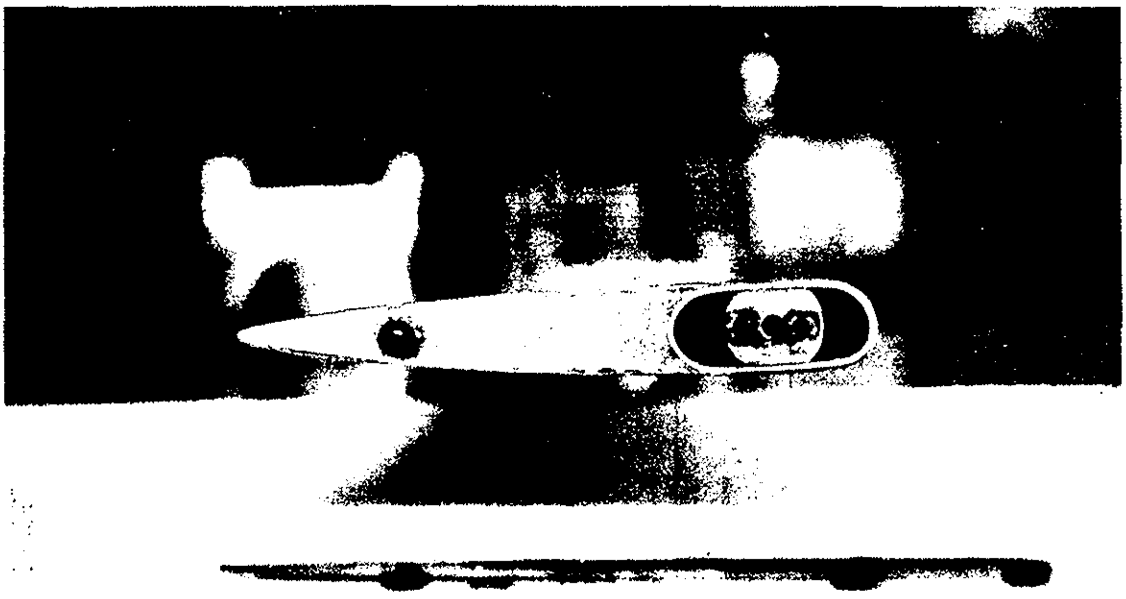

FIG. 5 BLADE CROSS SECTION

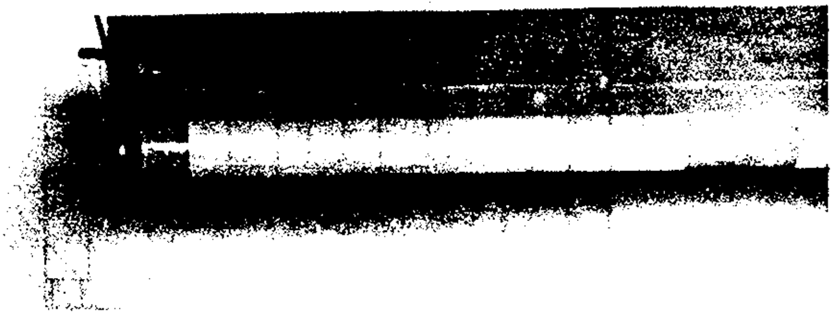

FIG. 6 BLADE WITH FLOW DEFLECTOR PLATE

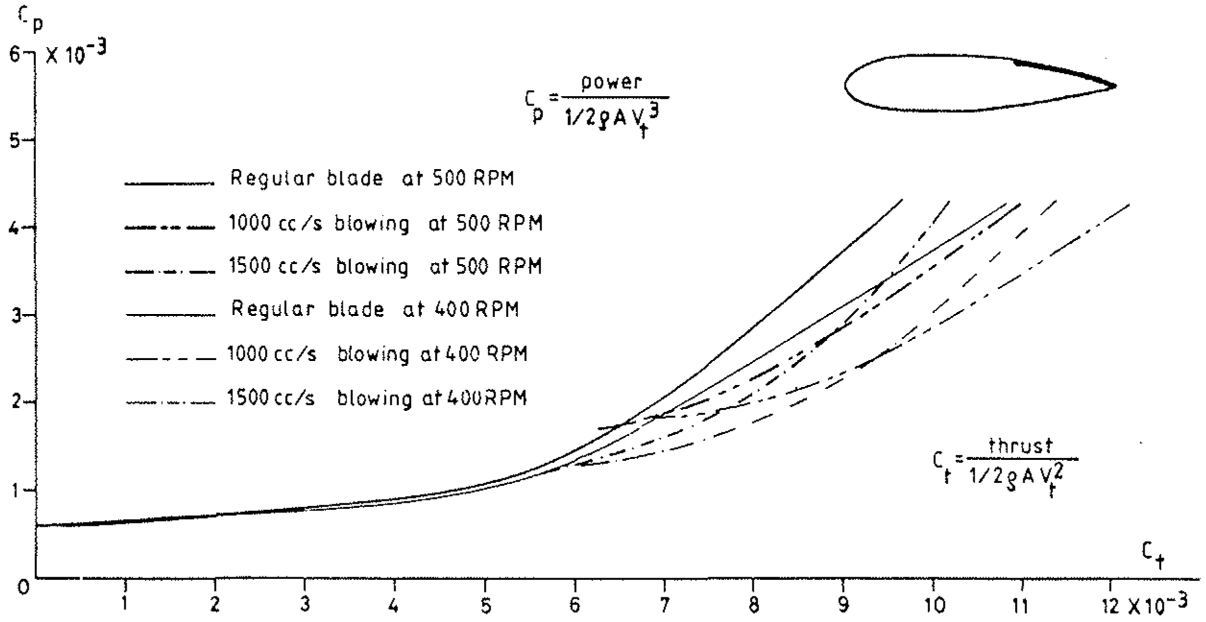

FIG. 7 EFFECT OF BLOWING AT 40% CHORD ON ROTOR HOVER PERFORMANCE

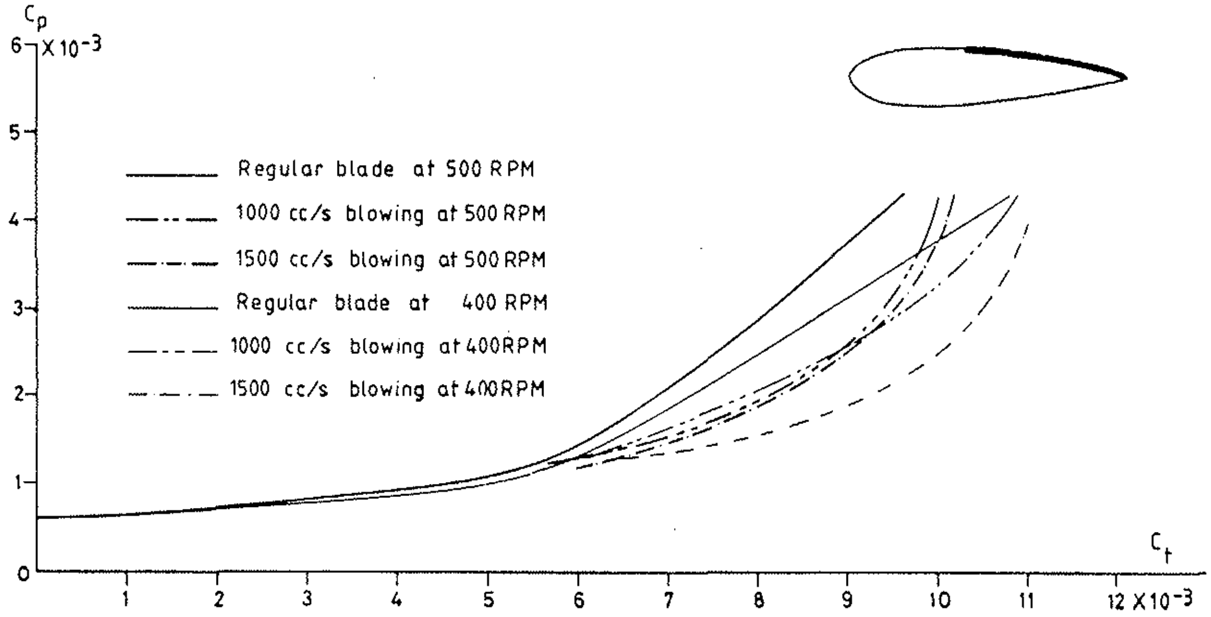

FIG. 8 EFFECT OF BLOWING AT 60% CHORD ON ROTOR HOVER PERFORMANCE

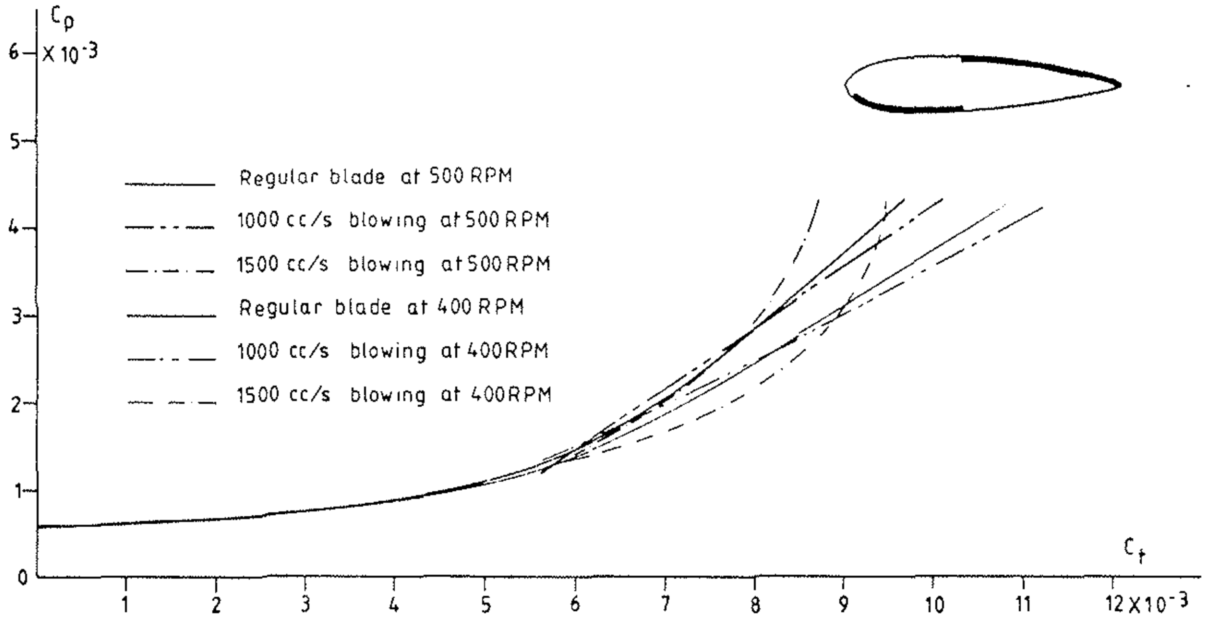

FIG. 9 EFFECT OF BLOWING AT 40/60% CHORD ON ROTOR HOVER PERFORMANCE

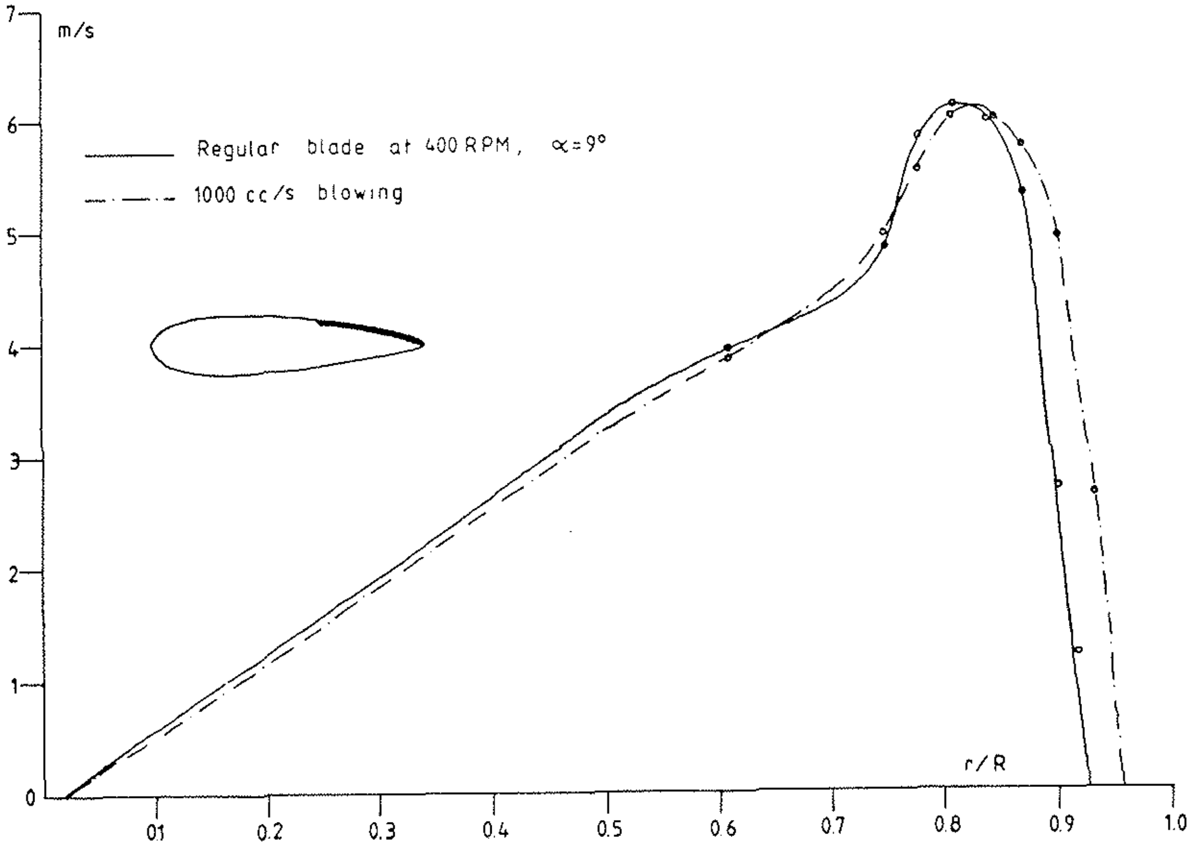

FIG. 10 EFFECT OF BLOWING AT 40% CHORD ON DOWNWASH DISTRIBUTION, 0.11R BELOW THE ROTOR

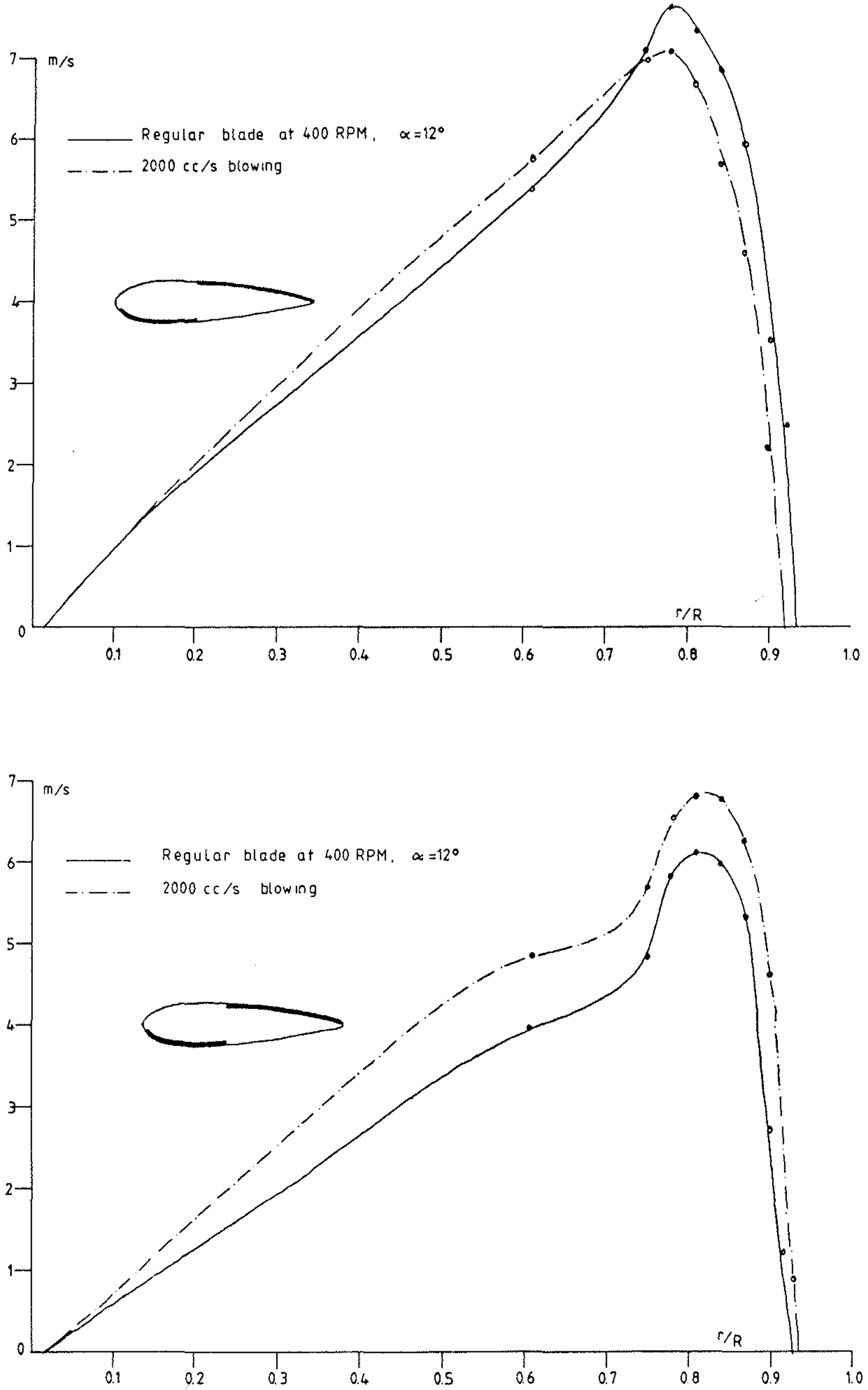

FIG. 11 EFFECT OF BLOWING AT 40/60% CHORD ON DOWNWASH DISTRIBUTION, 0.11R BELOW THE ROTOR

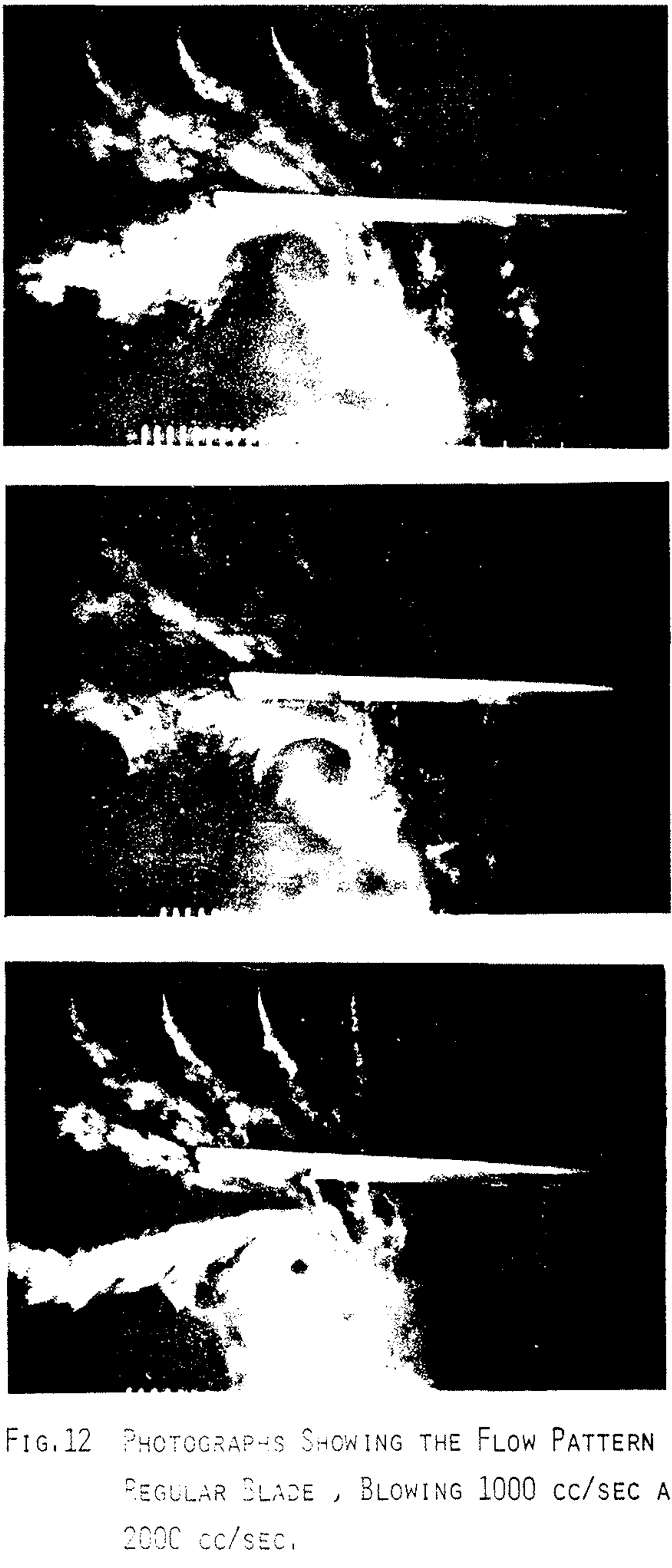

Fig. 12 Photographs Showing the Flow Pattern for the Regular Blade , Blowing 1000 cc/sec and Blowing 2000 cc/sec.