REPORT No. 322

INVESTIGATION OF AIR FLOW IN OPEN-THROAT WIND TUNNELS

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SUMMARY

Tests were conducted on the 6-inch wind tunnel of the National Advisory Committee for Aeronautics during May and June, 1928, to form a part of a research on open-throat wind tunnels. The primary object of this part of the research was to study a type of air pulsation which has been encountered in open-throat tunnels, and to find the most satisfactory means of eliminating such pulsations.

In order to do this it was necessary to study the effects of different variables on all of the important characteristics of the tunnel. This paper gives not only the results of the study of air pulsations and methods of eliminating them, but also the effects of changing the exit-cone diameter and flare and the effects of air leakage from the return passage.

It was found that the air pulsations in the 6-inch wind tunnel could be practically eliminated by using a moderately large flare on the exit cone in conjunction with leakage introduced by cutting holes in the exit cone somewhat aft of its minimum diameter.

INTRODUCTION

The wind tunnels which have been designed and built within the last few years, both at the Langley Memorial Aeronautical Laboratory and elsewhere, have been, to an increasing extent, of the open-throat type. This is due primarily to the greater ease of mounting and observing the models in this type of tunnel. The earlier experiments on wind tunnels in this country were made on tunnels of the Venturi type, so that there is little information available on which to base the design of open-throat tunnels of the Göttingen type. The need for such data is becoming more apparent as new tunnels are built in which it has been found difficult to secure the desired velocity and to satisfactorily control the air stream passing across the test section. In several open-throat tunnels violent pressure pulsations have been encountered. The exact cause of such pulsations is not yet definitely understood; however, the conditions under which pulsations are set up indicate that the phenomenon is very similar to the generation of pulsations in an organ pipe. Apparently the air in the jet alternately flows in and spills out around the mouth of the exit cone, causing alternate regions of compression and rarefaction in the exit cone and return passage traveling around the tunnel at the speed of sound. This action is regenerative, each compression wave in the exit cone causing more spilling, and vice versa, so that the pulsations may become very violent.

Experiments on the air flow in an open-jet tunnel to study the effect of various sizes, shapes, and spacing of cones were recently made by the National Advisory Committee for Aeronautics. (Reference 1.) The application of these results is somewhat limited because certain variables were not changed and because certain characteristics of the tunnel were not measured. Most important among the variables which remained constant throughout the previous investigation was the amount of air leakage from the return passage back to the test section. Since a considerable portion of the air which was taken in by the exit cone came from this source rather than from the entrance cone, the optimum size of exit cone and exit-cone flare there given would not be expected to apply to a tunnel having a different amount of leakage. During those tests no tendency toward pulsating flow was observed, probably because of the large amount of leakage.

Since the above-mentioned tests were made, the variable density wind tunnel of the National Advisory Committee for Aeronautics has been redesigned and rebuilt as an open-throat tunnel. It was possible to so design the tunnel that there would be practically no leakage. The exit cone was made small in view of the fact that no space would be required to provide for the reentrance of the leakage air, and also because it was thought that a large exit cone would tend to reduce the velocity downstream in the test section, thus causing an objectionable downstream pressure gradient. Very severe vibrations were encountered when the tunnel was in operation which at first were attributed to the elasticity of the steel structure. During a visit to the laboratory Professor Lesley of Stanford University became interested in the vibrations because of a similar effect which had been encountered in the Stanford tunnel. There it was discovered accidentally that objects protruding into the stream from the edge of the entrance cone reduced the pulsations. A similar experiment was made in the variable density tunnel by simply having four men hold their hands so that they projected into the air stream about 5 inches at the mouth of the entrance cone. This practically eliminated the most severe pulsations. Later eight metal tabs, 3 by 5½ inches, were installed in the tunnel. These were found to be very satisfactory in reducing the vibrations.

With the object of comparing this method of reducing the pulsations with other possible methods, the present investigation was started. Dealing primarily with air pulsations, it forms a part of a larger research now in progress on the design of open-throat wind tunnels. The investigation was conducted in the 6-inch wind tunnel of the National Advisory Committee for Aeronautics because of the comparative ease of constructing new parts for and making modifications to a small tunnel. The effect of the variables on the tendency toward pulsating flow could not be studied without regard to their effect on the other important characteristics of the tunnel. The investigation was therefore extended to include the effects of variables which were not covered in the previous investigations on all of the important characteristics of a wind tunnel. The following are the important variables considered:

1. Flare of exit cone.
2. Diameter of exit cone.
3. Obstructions at mouth of entrance cone.
4. Leakage from diffuser or return passage.

The effects of the above variables were studied with reference to the following characteristics of the tunnel:

1. Tendency toward pulsating flow.
2. Energy ratio.
3. Downstream pressure gradient.
4. Velocity distribution across the stream at the test section.
5. Velocity outside of the stream at the test section.
6. Velocity outside of the stream at the mouth of the exit cone.

APPARATUS

The tunnel used in this investigation, known as the 6-inch wind tunnel, is shown diagrammatically in Figure 1, and described in detail in references 1 and 2. During the present series of tests the diameter of the jet was $6^{13}/_{16}$ inches and the distance between the entrance cone and exit-cone flare was one diameter ($6^{13}/_{16}$ inches). The exit cone consisted of a steel cone slightly over 3 feet long tapering from the variable minimum diameter to the propeller diameter, 12¼ inches. The air was returned to the entrance cone through a single rectangular return passage having guide vanes in the corners. Various shapes of exit-cone flares of wood could be slipped on over the mouth of the metal exit cone. (Fig. 1.)

To study the effect of the exit-cone flare two types were used, designated F_1 and F_2. These, together with a third type designated F_3 and later tested, are shown in Figure 2. F_1 was modeled after the flare in the variable-density tunnel and F_2 and F_3 were larger.

To study the effect of exit-cone diameter, exit cones with the various amounts of flare were constructed having three different minimum diameters. The smallest one, designated E_1, was modeled after the variable-density tunnel cone. E_2 was three-sixteenth inch larger in diameter and E_3, the largest, was chosen to give the same divergence angle from the mouth of the entrance cone to the throat of the exit cone as that in the propeller research tunnel of the National Advisory Committee for Aeronautics. Figure 2 is a scale drawing of these cones giving the important dimensions.

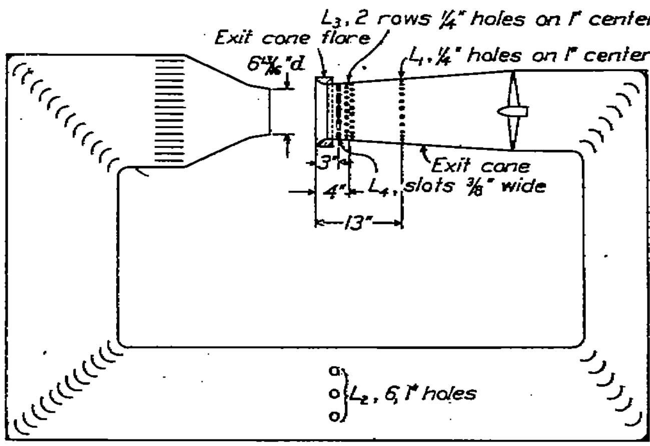

FIGURE 1.—Diagrammatic sectional elevation of the 6-inch wind tunnel

Small rectangular metal tabs projecting into the stream from the mouth of the entrance cone were also included among the variables because such obstructions in the mouth of the variable-density tunnel had a tendency to reduce the air pulsations. The effect of eight tabs 3 inches wide and 5½ inches long had been verified in the variable density tunnel; consequently, scale models of these tabs were used in connection with these tests.

The fact that previous experiments which had been conducted on the same tunnel before it was made air-tight, indicated no pressure pulsations led to the belief that a small leakage of air between the return passage and the test section would have a stabilizing effect on the flow. Preliminary runs were made to study qualitatively the effects of leaks and to determine what leaks should be included in the systematic investigation. As a result, two sets of holes were drilled in the exit cone between the test section and the propeller and one set of holes behind the propeller in the center of the return passage. The investigation included tests with different combinations of these holes opened, together with the various flares and exit-cone diameters. These leaks have been designated L_0, L_1, L_2, L_3, etc. The location and size of each set of leaks is shown diagrammatically in Figure 1.

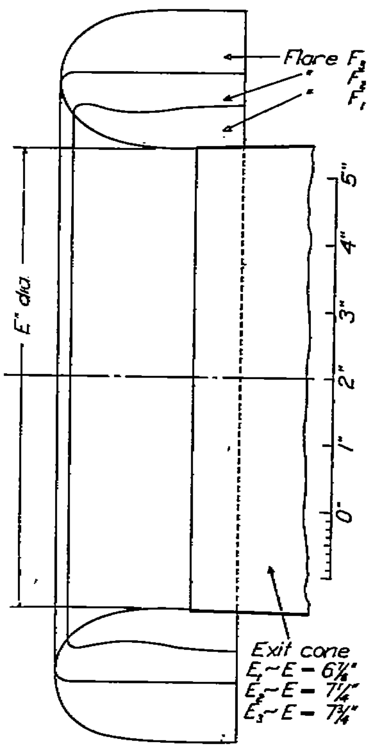

FIGURE 2.—Superimposed diagram of flares. The entrance cone shown on Figure 1 is $6\frac{15}{16}$ inches diameter

TESTS

With each set of conditions a set of runs was made to determine the characteristics of the tunnel. The tendency toward pulsating flow was measured, after adjusting the air speed in the tunnel until the audible pulsations became loudest, by taking a pressure-time record on a recording photomanometer connected to the return passage by means of a 4-inch length of ¼-inch tubing. The energy ratio was obtained by measuring the power input to the driving motor corresponding to a given pressure head as measured on a manometer which was connected to a static plate in the large part of the entrance cone. The velocity distribution across the stream and the static pressure gradient downstream were determined by means of a small Pitot-static tube and alcohol manometer.

A comparative figure indicating in a rough way the magnitude of the balance windage corresponding to each set of conditions was obtained by means of a hot-wire anemometer. The hot wire was held in position corresponding to the balance in the variable density tunnel; that is, 1 inch and 2 inches from the edge of the jet, 0.3 diameter from the entrance cone edge.

Readings to determine spilling velocity were also taken with the hot wire held one-fourth inch and 1 inch away from the edge of the exit cone flare.

RESULTS

The results of the investigation are presented in the form of groups of curves so arranged on one sheet that the curves in the vertical columns represent constant leakage and variable exit cone diameter and flare. The diameter and flare of the exit cone increase from the top of the sheet to the bottom. The curves in the horizontal columns represent different degrees of leakage beginning with minimum leakage at the left. The last vertical column in Figures 3 and 4 gives the results of the test with tabs on the mouth of the entrance cone.

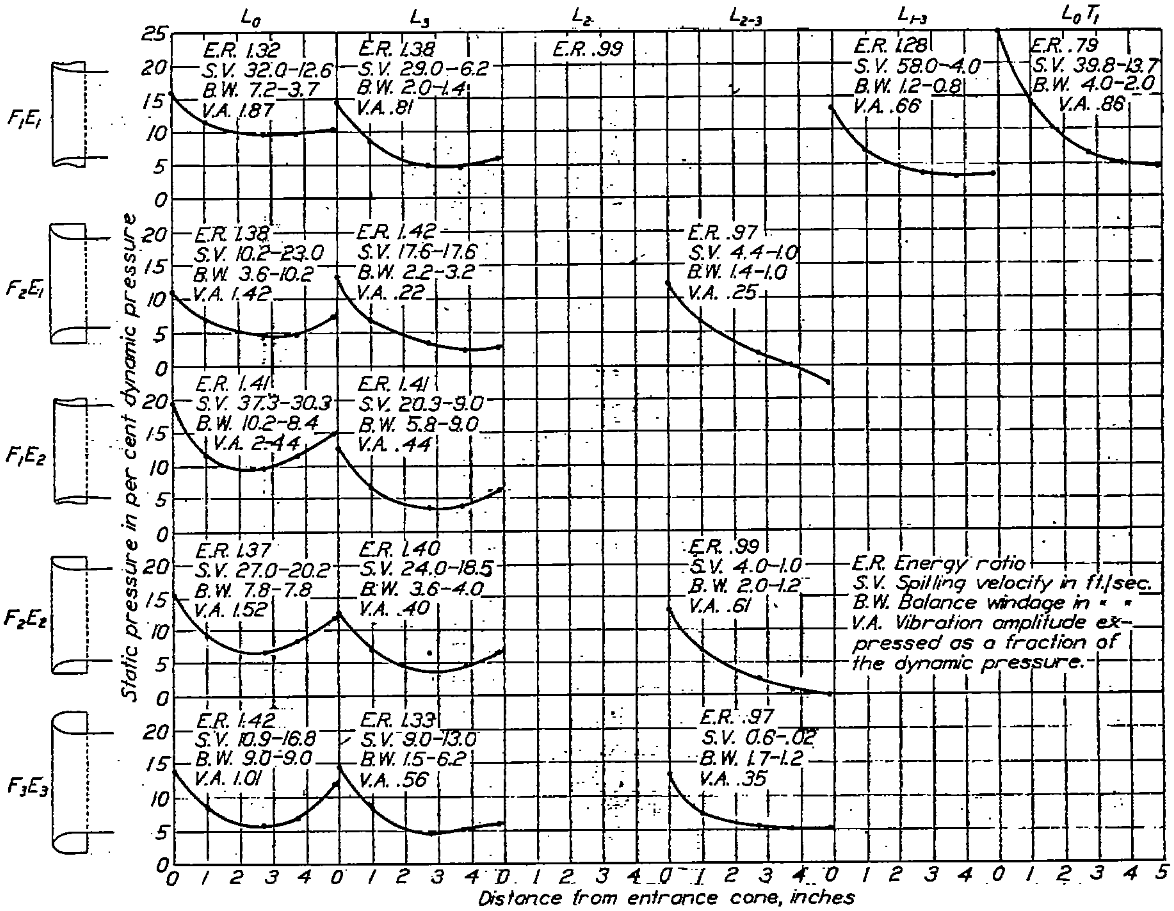

FIGURE 3.—Curves of static pressure in per cent of dynamic pressure measured at test section in the center of the jet plotted versus distance from entrance cone in inches

In this manner, in Figure 3, the curves of static pressure in the center of the jet are plotted against the distance from the mouth of the entrance cone in inches. The static pressure is given in per cent of the dynamic pressure at the test section so that the curves indicate the variation in velocity along the stream as well as the buoyancy which may be expected on a model. On each plot are also given numbers which represent the other characteristics of the tunnel. Opposite E. R. is given the energy ratio of the tunnel; that is, the ratio of kinetic energy of the air passing through the test section in one second to the electrical input power to the driving motor. Opposite S. V. two figures are given which measure roughly the spilling velocity around the mouth of the exit cone in feet per second. The first is the velocity one-fourth inch outside of the outer lip of the exit cone and the second, 1 inch outside. The figures opposite B. W. are indicative of the balance windage. The figures indicate the air velocity in feet per

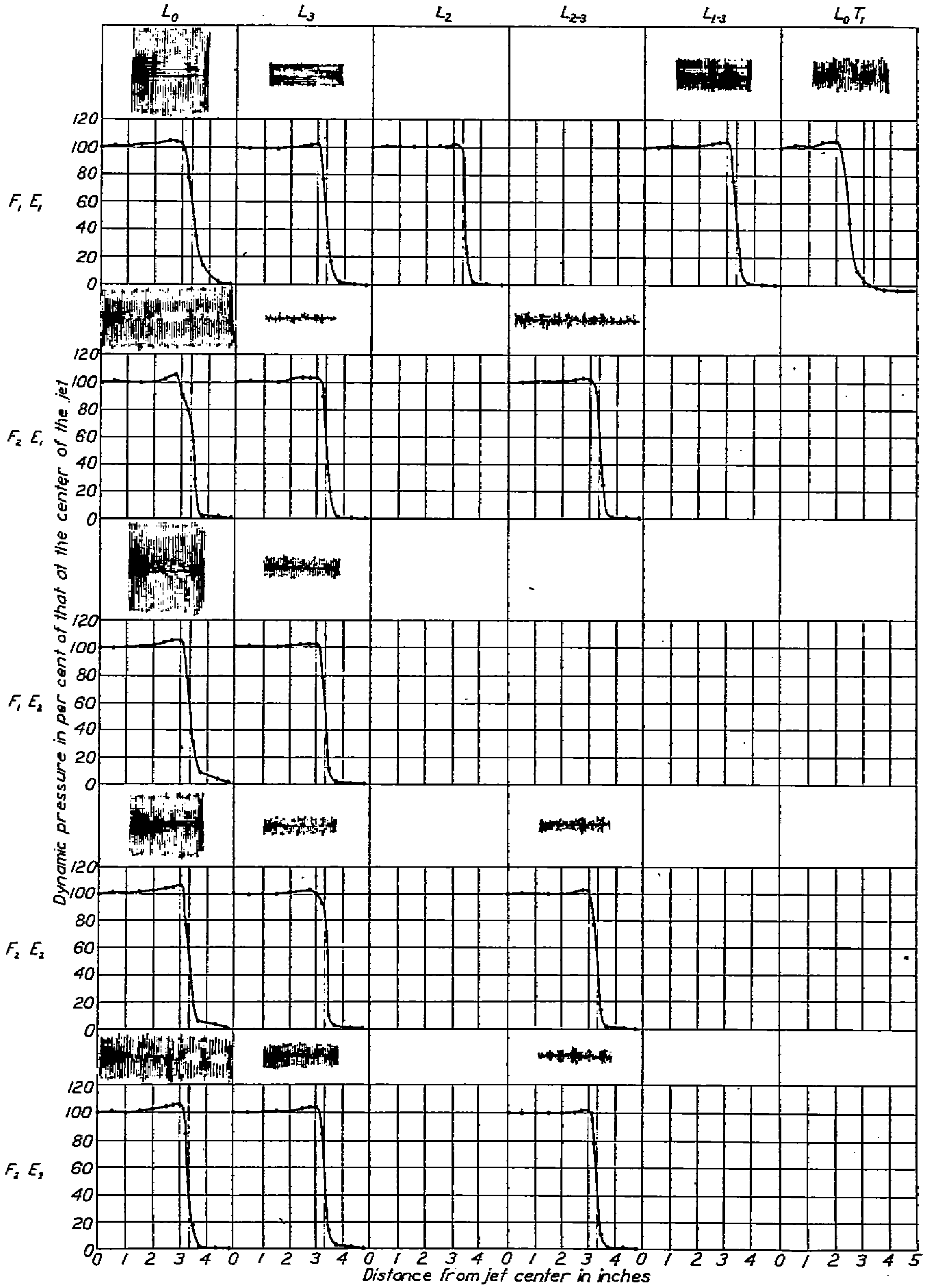

FIGURE 4.—Curves of dynamic pressure across air stream at test section versus distance from jet center in inches. Vertical line indicates entrance cone edge. Pressure records taken in return passage to show air pulsations

second as measured at points 1 inch and 2 inches, respectively, from the edge of the jet, 0.3 diameter aft of the edge of the entrance cone. Opposite V. A. is given the average vibration amplitude as measured on the photomanometer connected to read the static pressure in the return passage. The amplitude is expressed as a fraction of the dynamic pressure in the test section.

In Figure 4, arranged in the same order, are given the results of the dynamic pressure surveys across the air stream at the test section. The dynamic pressure as read from a Pitot-static tube in per cent of the dynamic pressure at the center of the air stream is plotted against the distance from the center of the stream in inches. The vertical lines on the graphs represent the position of the edge of the entrance cones. On each plot is also given a part of the photomanometer record of the static pressure in the return passage.

Figure 5 gives the results of further investigations confined to the smallest diameter exit cone. The results produced by other leaks and by a larger flare, investigated with a view to

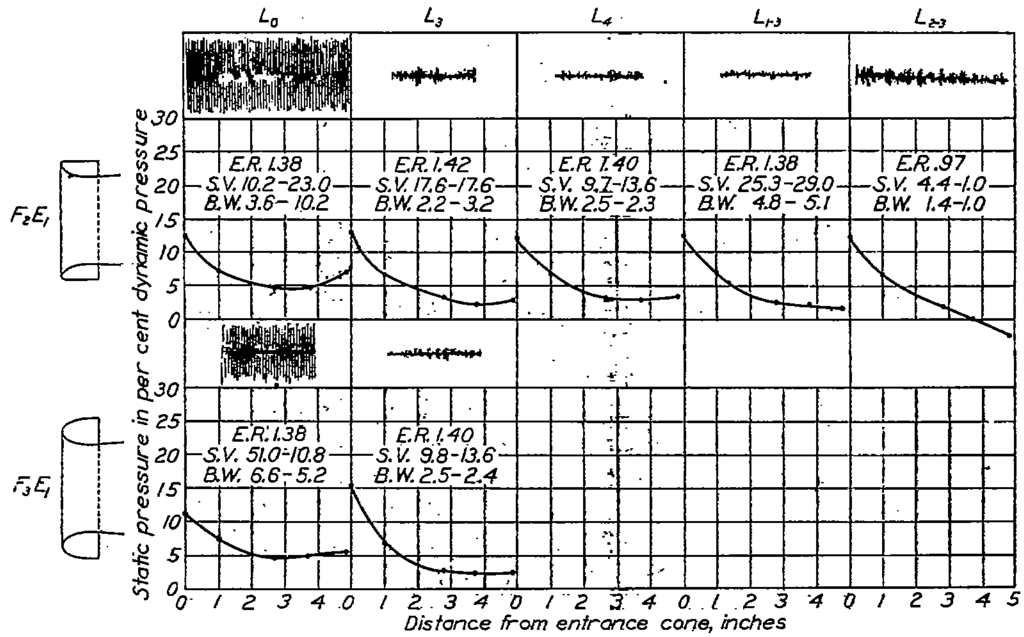

FIGURE 5.—Curves of static pressure and return passage pressure records

solving the problem of pulsations in the variable density wind tunnel, are included, together with other data already given, to complete the figure.

DISCUSSION

Exit-cone diameter.—The effect of exit-cone diameter on the characteristics of the tunnel, as expected, depends to a great extent on the leakage of air from the return passage. An examination of the first vertical row of Figures 3 and 4 shows that from the standpoint of downstream static pressure gradient a small exit cone is desirable when the leakage is small, because the large cones tend to reduce the velocity and increase the static pressure downstream. With a large amount of leakage the opposite is true, the increasing static pressure from the larger cones tending to offset the head lost in accelerating the leakage air as it is picked up by the jet. Enlarging the exit cone has no other marked effect on the characteristics of the tunnel except to reduce the pulsations slightly when little leakage is present and to reduce the spilling velocity in some cases.

Exit-cone flare.—The effect of increasing the exit-cone flare is much the same as the effect of increasing the exit-cone diameter except that, with a small amount of leakage, increasing the flare is much more effective in reducing pulsations.

Leakage from the return passage.—Leakage has a very marked effect on all of the characteristics except on the velocity distribution across the air stream. Leakage from any part of the return passage between the propeller and the entrance cone, while having some beneficial effects in some respects, produces, in all cases, a large reduction in energy ratio. In Figure 6 are given curves of the energy ratio before and after the tunnel was made air-tight. Previously the tunnel was constructed of wood and although it was as air-tight as might be expected, a velocity survey in the exit cone ahead of the propeller indicated that appreciably more air passed into the propeller than came out of the entrance cone. After lining the inside of the tunnel with doped fabric the other curve of energy ratio in Figure 6 was obtained. The latter condition of the tunnel is that designated as L_0 throughout this report and represents a very small amount of leakage.

Three possible reasons are advanced for the effect of leakage on the air pulsations. First, the leakage air forms a sort of cushion surrounding the jet, directing it uniformly into the center of the exit cone. Second, the natural inflow of air around the jet, with leakage, is continuous, whereas without leakage the inflow is apt to continue after the tunnel has become sufficiently filled, resulting in later spilling from the exit cone. Air pulsations would result from a continuous repetition of these events. Third, if violent pressure pulsations should be set up in a leaking return passage, a considerable amount of energy would be dissipated by the air flowing back and forth through the leaks. They would, therefore, have a damping action on the pulsations.

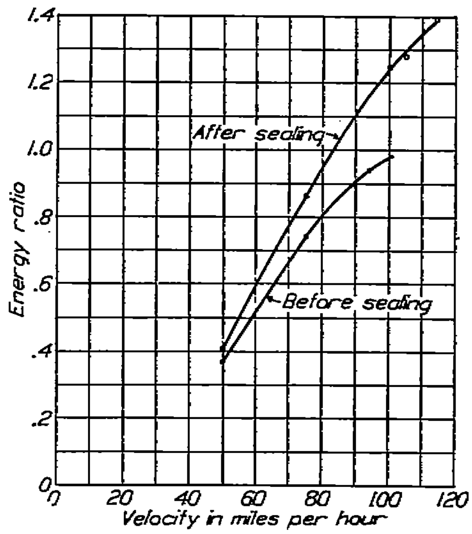

FIGURE 6.—Energy ratio before and after sealing

The results of these tests indicate that the beneficial effects of leakage may be realized without sacrificing the energy ratio by placing the leaks where the pressure difference across them is low so that the energy loss will be small. Introducing leaks in the exit cone ahead of the propeller probably has another effect which may partially compensate for the energy dissipated in them. Such leaks tend to remove the boundary layer along the sides of the exit cone, thus stabilizing the flow and increasing the efficiency of the exit cone as a diffuser. (Reference 3.) Figure 3 indicates this effect, the leaks L_3 which consist of two rows of one-fourth inch holes spaced 1 inch apart near the mouth of the exit cone, when used with the smaller diameter exit cone and the large flare, practically eliminated the pulsations and at the same time improved the energy ratio slightly. The same leakage with the larger exit cone diameters was not so effective in reducing the pulsations, because a smaller amount of air was discharged through the holes.

Entrance-cone tabs.—Tabs or obstructions at the mouth of the entrance cone, such as those used in the variable density tunnel, need not be considered as a practical means of reducing pulsations. Not only are the other characteristics of the tunnel imparied, as shown in the upper right-hand plot of Figures 3 and 4, but the pulsations are not sufficiently reduced.

Tendency toward pulsating flow.—The pulsating flow may sometimes be eliminated or reduced by changing the air speed in the tunnel. During these tests it was found that the pulsations existed over a considerable portion of the speed range. Above the speed at which the records were taken the pulsations practically ceased and then came in again at a higher speed with twice the original frequency. The frequency of the pulsations apparently depends on the size of the tunnel and not on the speed of the tunnel propeller. The records given in Figure 4 show a pulsation frequency of 79 cycles per second, whereas the propeller speed varied from one test to another between 48 and 58 r. p. s. Should the tunnel air speed be variable or should the pulsating flow not come at the speed at which tests are made, it is still desirable to design new tunnels so that this difficulty will not be encountered. This may be accomplished by simply providing a rather large exit cone and flare if the return passage leaks considerably, the size of the exit cone depending on the amount of leakage present. If the tunnel passages are air-tight the tendency toward pulsating flow may best be avoided by providing holes in the exit cone slightly behind its mouth or bell L_4, fig. 1) and using an exit cone having a large flare and an only slightly larger diameter than the entrance cone.

Downstream pressure gradient.—This characteristic of a tunnel, while not always of great importance, is here considered because of its effect on testing airships and because it indicates the uniformity of the velocity downstream. The static pressure in the center of the jet at the mouth of the entrance cone was in all cases higher than the pressure of the air surrounding the jet by more than 10 per cent of the dynamic pressure. From this point aft the pressure in the stream dropped at a rate which increased with the amount of leakage. The larger flares and exit cone diameters caused the pressure to rise again as the air approached the exit cone. Therefore, if the amount of leakage is very small, the most uniform static pressure may be secured by using a small exit cone and small flare. If a large amount of leakage is present, it is necessary to use a large exit cone and flare to secure a reasonably uniform static pressure. The large static pressure near the mouth of the entrance cone and the resulting high gradient is probably characteristic of the rather short entrance cone.

Velocity distribution across the air stream.—The dynamic pressure surveys given in Figure 4 were taken across the stream at the position at which models are usually placed, i. e., 30 per cent of the opening behind the mouth of the entrance cone. The results show that at this diameter the velocity distribution is little changed by any of the variables considered except by the tabs which were placed on the entrance cone. The velocity distribution is undoubtedly determined primarily by the shape of the entrance cone, form of the return passage, and position of the honeycomb. All of the surveys show a peculiar high velocity region just inside of the edge of the jet. Otherwise the dynamic pressure is reasonably uniform across the test section under all conditions.

Energy ratio.—The energy ratios based on electrical power input to the motor varied between 1.42 and 0.79. The lowest energy ratio was obtained when the tabs were used on the entrance cone. When leaks were introduced in the return passage the energy ratio was reduced about 40 per cent; otherwise variations in the energy ratio were small.

Spilling velocity.—The figures (opposite S. V. in figs. 3 and 5) representing velocity in feet per second outside of the exit-cone flare, show the difference between the various arrangements in regard to air disturbances around the exit cone. The air flow in this region was found to be very unsteady and difficult to measure so that these figures should be taken only as a rough comparison between different conditions. They show, however, a definite tendency toward lower spilling velocities as the exit cone diameter and flare are increased and an even more marked reduction as the amount of leakage is increased.

Balance windage.—The balance windage, like the spilling velocity, is expressed by figures indicating roughly the velocity in feet per second, which may be expected in the region of the balance. These measurements were difficult to make and appear to be somewhat erratic. In general, it appears that the balance windage will be considerably reduced by the introduction of leakage. In any particular tunnel the balance windage depends on other factors, such as the position of the balance and the shape of the test chamber, so that these results should not be taken as applying to all open-throat tunnels.

CONCLUSIONS

Throughout this series of tests only those variables were investigated which were believed to have an immediate effect on pulsations in the air flow. All of the results may not be applicable to other types of open-throat tunnels, but the following conclusions will probably always be true:

1. Air pulsation in open-throat tunnels may be practically eliminated by introducing leaks between the return passage, or exit cone, and the test section if a large flare is used on the exit cone

2. Leakage from the return passage may cause a large reduction in the energy ratio. However, if the leakage is from a point near the mouth of the exit cone, where the pressure difference is small, the loss in energy is negligible.

3. The velocity distribution across the stream at the test section is little affected by either leakage or shape and size of the exit cone.

Langley Memorial Aeronautical Laboratory,
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