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Tapered Resonance Tubes: Some Experiments

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Introduction

IN 1916 Hartmann[1] discovered that under appropriate conditions intense noise emanated from, and pressure oscillations were produced in, shallow circular-cylindrical cavities of uniform cross-sectional area placed in sonic airjets. Now known as the Hartmann whistle, this device has been subjected to extensive investigation directed towards improvement of its acoustic efficiency[2] (Fig. 1a).

In 1954 Sprenger[3] discovered that under appropriate conditions a very slender Hartmenn whistle, with a length-to-diameter ratio, l/d, of 34 in contrast to a nominal l/d of about 4, exhibited intense heating at the closed end. Now known as the resonance tube, (Figure 1b), this device is a less efficient noise generator than the Hartmann whistle, but is of interest due to its heating characteristics. Sprenger recorded average resonance tube end-wall temperatures as high as 840°F with clean air and 1830°F when solder particles were accidentally introduced into the driving airstream. The generation of temperatures several times greater than the freestream stagnation temperature by a simple passive device appears to be unique.

It is believed that the underlying aerodynamic resonance phenomenon might contribute, under certain conditions, to enhanced meteorite "pitting" and ablation of heat shields on atmospheric re-entry vehicles, as well as thermally induced structural failure in a number of devices of technological interest, e.g., pneumatic systems. Further, it represents a potential explosion hazard, as has been recognized in the past.[4] Simple laboratory experiments illustrate graphically this aspect. For example, a small slug of wood placed in a resonance tube will ignite and burn vigorously in a few seconds.[3,4] Indeed, there has been an attempt to harness this explosive potential in a passive ignition system for hydrogen-oxygen rocket engines.[5]

All previous investigations of the phenomenon known to the authors were restricted to resonance tubes of uniform cross section along the entire length. By contrast, the subject study dealt primarily with tubes that were unique by virtue of having cross-sectional area distributions which decreased continuously from the open mouth to zero area at the closed end, i.e., tapered tubes (Fig. 1c). In practical situations that hold explosion hazards, such as incipient failure of pneumatic system seals, it is believed that tapered resonance tubes approximate the actual geometries better than do the conventional tubes previously studied.

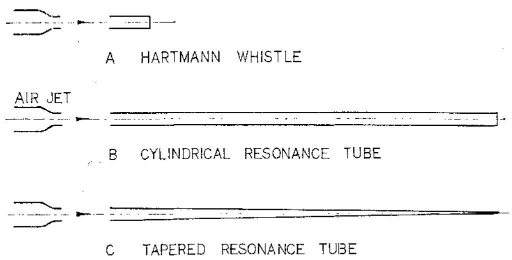

Fig. 1 Schematic of Hartmann whistle and resonance tubes.

Aerodynamic Phenomena of the Uniform Cross Section Resonance Tube

Instability has been found to be excited by sonic and supersonic airjets[6] and by subsonic and supersonic wind-tunnel flows. The most widely used method of excitation for experimental investigation has been sonic airjets.

The first realistic description of the fully developed flow within conventional resonance tubes was produced by Thompson.[6] By using a correctly expanded supersonic airjet he produced experimentally well-defined boundary conditions at the mouth, which enabled him to construct a wave diagram for the internal flowfield. This was well supported by experimentally observed pressure histories and flow patterns within the tube.

Thompson and others observed that the conventional tubes resonated at approximately the acoustic (simple organ pipe) frequency based on the freestream stagnation temperature. During part of the cycle some of the airjet gas is ingested, and much of the same gas is expelled during the remainder of the cycle. Thus, a slug of indigenous gas is trapped near the endwall for many cycles.

On every cycle a system of shock waves and expansion waves of nonuniform strength transit the indigenous slug. As the local entropy increase during compression is greater than the local decrease during expansion, it follows that the net thermal effect of a cycle is to produce an incremental increase of local temperature. Since resonance tubes operate at several hundred cps, even a small temperature increment per cycle can result in rapid heat-up of the indigenous gas; in extreme cases reaching temperatures far in excess of 1000°F within several seconds. No valid means of predicting resonance tube thermal effects are known to the authors. For example, not even the maximum temperature theoretically possible in the adiabatic situation, i.e., no heat loss to the surroundings from the tube, can be realistically predicted.[8]

Description of the Experiment

A variety of combinations of airjet velocity, ratio of airjet nozzle diameter to resonance tube diameter, resonance tube l/d, and separation between airjet nozzle and tube mouth have been found to produce the aerodynamic resonance of interest.[3] As the thermal effects were of prime interest in the present study, a configuration was selected that maximized it. That is, an airjet, produced by expanding from stagnation conditions of 70 psig and 70°F through a converging nozzle of $\frac{5}{16}$ in. diam to the atmosphere, was used for driving axially aligned tubes of $\frac{5}{16}$ in. diam area located $1\frac{1}{4}$ in. away. The tubes were all about $10\frac{1}{4}$ in. long. (Experimental details are

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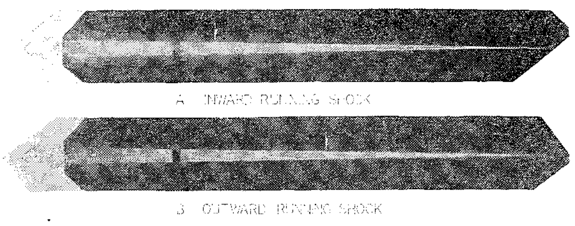

Fig. 2 Shadowgraphs of 2-dimensional tapered resonance tube operation (vertical shadow cast by external structural member).

presented in Ref. 9.) A rectangular cross section was employed for photographic observations in both the tapered, i.e., wedge, and conventional configurations. Also, a circular cross section was employed in both the tapered, i.e., conical, and conventional configurations used in studies of thermal effects.

The data obtained during this operation included: pressure histories obtained by means of rapid-response-time piezoelectric transducers; experimental wave diagrams produced from an amalgam of individual shadowgraphs of the internal flow taken at successive times in the resonance period (a variable delay circuit between the pressure transducer output and shadowgraph spark-light permitted efficient gathering of these data), spectral analysis of noise generated, temperature histories by means of thermocouples and rapid-response-time, thin-film, resistance thermometers, and ignition characteristics of some organic materials inserted in the tube.

Experimental Results

The following is a summary of the experimental results:

1) Conditions required to produce resonance in tapered tubes were approximately the same as in conventional tubes, and the exterior flowfields were very similar.

2) Tapered tubes produced slightly higher noise levels than conventional tubes of equal length (142 db vs 136 db) but they resonated at a 50% greater frequency.

3) Shadowgraphs taken during the operation of the wedge-shaped tube indicate that the leading shock wave formed during the inflow portion of the cycle was curved (Fig. 2a); and also that turbulence was generated by passage of the exiting shock wave (Fig. 2b).

4) For the wedge-shaped tube, Fig. 3 shows that the inward running shock wave (depicted in Fig. 2a) increases in velocity with decreasing tube area, but that the shock wave that runs out the tube (Fig. 2b) remains at constant velocity even though the tube area increases. (Expansion waves are present during tube operation, but are not depicted in Fig. 3.)

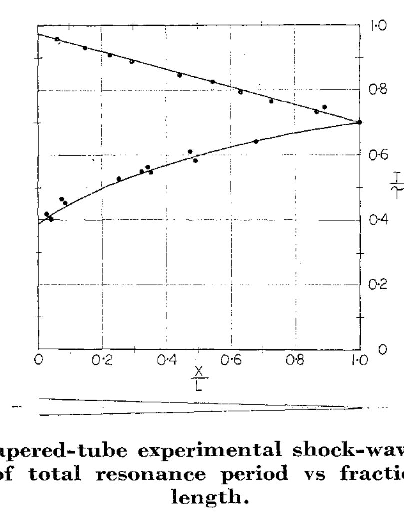

Fig. 3 Tapered-tube experimental shock-wave diagram: fraction of total resonance period vs fraction of tube length.

5) For tubes of uniform cross section, the endwall surface temperature history was similar to the endwall pressure history.

6) The mean temperatures near the endwall of both conical and conventional resonance tubes (constructed from heavy-wall, in. $\frac{5}{8}$ o.d., Pyrex tubing), detected by means of $\frac{1}{25}$ in. diam. thermocouples inserted through their mouths were: 1050°F for the conventional tube when the end was protected from the cooling action of the airjet blowing along the outside of the tube, 1340°F before the unprotected conical tube softened, expanded, and burst. (Pyrex softens at 1200–1300°F.[10])

7) Solid blocks of wood and nitrate-ester rocket propellants were easily ignited within conventional resonance tubes. Other organic materials, in the form of liquid or loose powder, were blown out of conventional tubes before ignition could take place. However, tapered tubes tend to trap powders at the tip. And polystyrene powder, which was found to ignite readily and burn in the open atmosphere, was found to ignite readily and burn spectacularly in a tapered resonance tube. These results are presented in detail in Ref. 9.

Conclusions

Similarity in over-all behavior of resonance characteristics for all tubes tested, both conventional and tapered, demonstrates that internal geometry is not an important factor in either initiating or sustaining the phenomenon. As had been suggested previously,[6] events that take place near the tube mouth probably are of critical importance.

Both the observed curvature of the inward propagating shock, and the remarkable independence of outward propagating shock velocity on changing cross section area (Fig. 3), suggest that one-dimensional models are probably too simplistic to describe the process realistically.

Thermal and other effects are intensified by tapering resonance tubes, and consequently, the explosion hazard associated with naturally occurring geometries is greater than that indicated by experience with conventional resonance tubes. Ignition of various materials in resonance tubes demonstrates the reality of this hazard.

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