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ACOUSTIC EMISSION OF CAVITIES IN
SUPERSONIC AIRFLOW

by

M. G. Morozov

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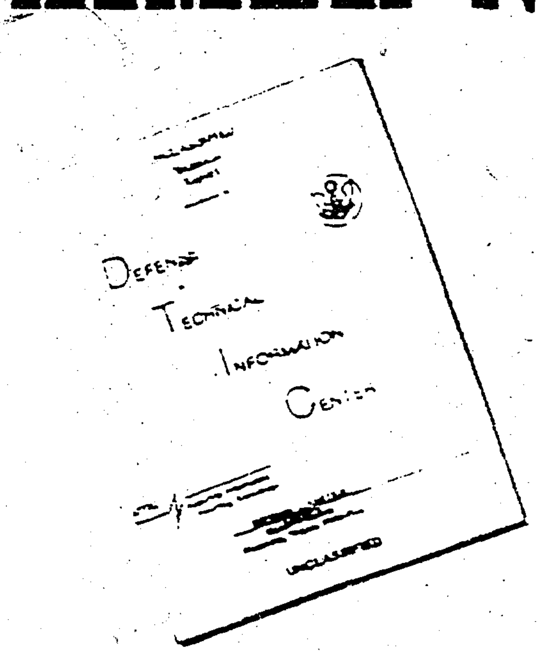

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ACOUSTIC EMISSION OF CAVITIES IN SUPERSONIC AIRFLOW

By: M. G. Morozov

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ABSTRACT This work gives the results of an experimental investigation of acoustics emission of cavities of diverse configuration on a flat plate in a supersonic streamline flow of air at M = 1.7.

From the investigation it is concluded that travelling waves on the interface result from the appearance of natural oscillations in a system consisting of the interface and the volume of air in the deepening.

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

ACOUSTIC EMISSION OF CAVITIES IN SUPERSONIC AIRFLOW

M. G. Morozov

(Moscow)

Below are results of experimental investigation of acoustic emission of cavities of diverse configuration on a flat plate, in supersonic airflow with M = 1.7.

1. Experimental installation and models. Experiments were conducted in a supersonic wind tunnel of continuous action at rated M = 1.7. In the work there was used a closed working part with section 27 × 27 mm, in which the model played the role of lower wall. For creation on the surface in the flow of single rectangular depressions of different configurations there was used a model allowing shift of individual parts to set different values of vertical, h, and longitudinal, l, dimensions of the depression. The distance from the blade of the plate to the leading edge of the depression, L, remained constant. A description of this model and the characteristic of the working part can be found in [1].

For investigation of the influence on acoustic emission of the state of the boundary layer and the form of depression and for study of the flow around a number of consecutive depressions there were used models constituting metallic plates with notches milled on the surface.

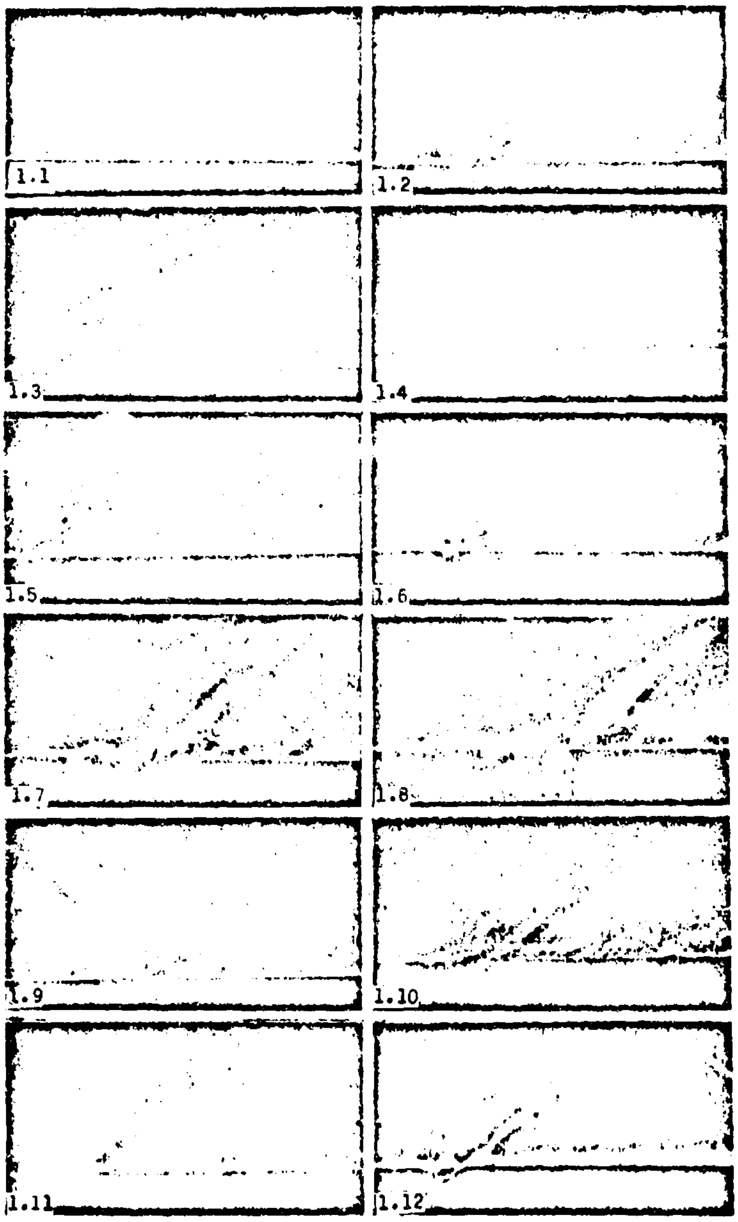


Fig. 1. Schlieren photographs. Flow is left to right. 1.1 — $h = 3.2$ mm, $l = 1.6$ mm; 1.2 — $h = 3.2$ mm, $l = 9.8$ mm; 1.3 — $h = 3.2$ mm, $l = 9.8$ mm; 1.4 — $h = 5$ mm, $l = 5$ mm; 1.5 — $h = 5$ mm, $l = 5$ mm; 1.6 — $h = 5$ mm, $l = 10$ mm; 1.7 — $h = 5$ mm, $l = 20$ mm; 1.8 — $h = 7$ mm, $l = 28$ mm.

In the process of experiments photographs of the flow were taken with the help of a Toepler-Maksutov IAB-451 with exposure of the order of $2 \cdot 10^{-3}$ and with application of a spark installation with exposure of less than $1 \cdot 10^{-6}$ s. All Fig. 1 photographs were obtained with the blade in the lower horizontal position.

2. <u>Rectangular depressions</u>. Figures 1.1-1.8 depict photographs of flow around single rectangular depressions with various values of l and h.

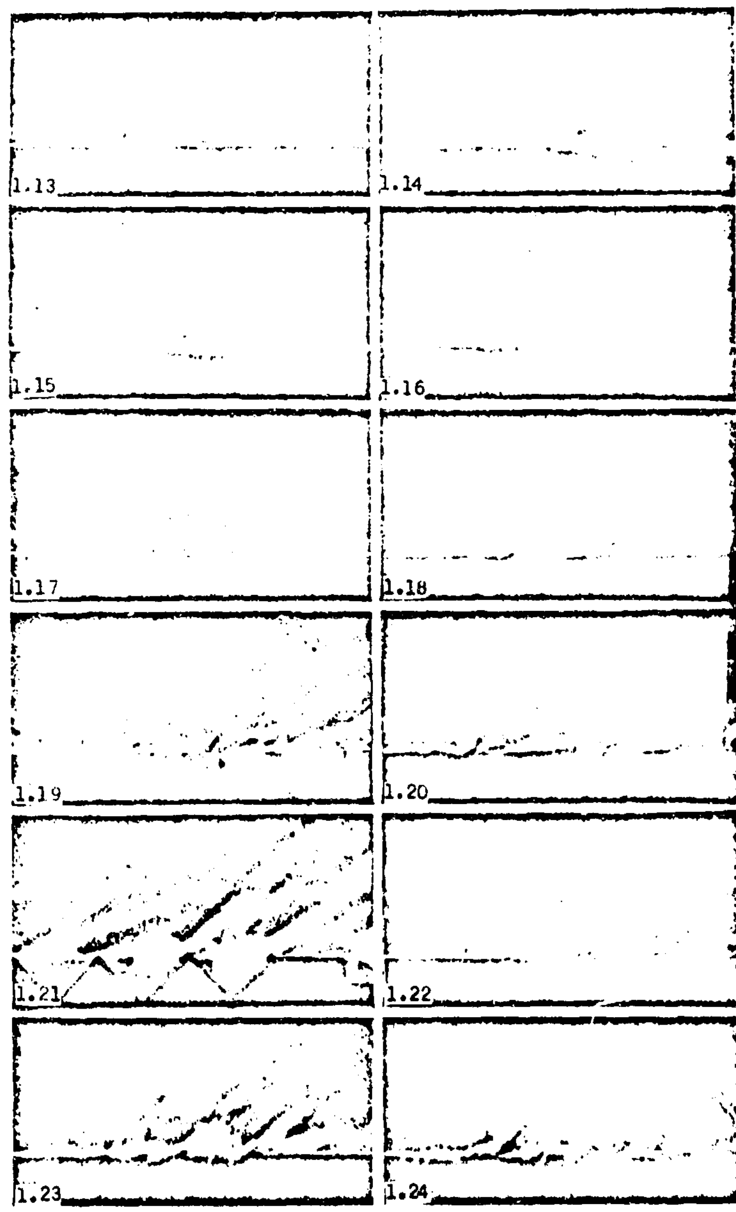


Fig. 1. (Continuation).

The boundary layer before separation from the leading edge of the depression in this case was laminar with a thickness of the order of 0.5 mm. The Reynolds number corresponding to the state of the boundary layer before breakaway and calculated from parameters of air at temperature of wall was equal to $R = 1.2 \cdot 10^5$.

On certain photographs there are seen disturbances reaching the plate from the cut of the nozzle and the edge of the plate. Measurements conducted by a probe of static pressure, the character of interaction of these disturbances with laminar boundary layer, and the character of their mutual intersection and intersection with other disturbances permit drawing the conclusion that their intensity is low. Below, their influence is not taken into account.

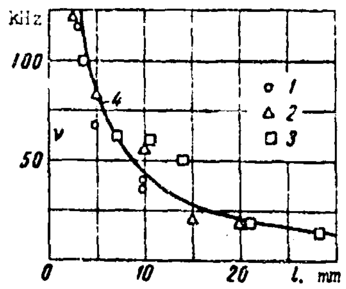
The most characteristic parts of the picture of flow around the depressions are bundles of acoustic waves in the form of regularly alternating light and dark lines going out from the depression in a band approximately corresponding to the length of the latter (Figs. 1.2, 1.3, and 1.5), the periodic structure of the boundary layer fixed on certain photographs behind depressions (Figs. 1.2, 1.3, 1.4, and 1.6) and bends of boundary (zone of mixing) between the volume of air in the depression and external flow (Figs. 1.3, 1.4, and 1.8). To facilitate further analysis, Fig. 2 gives a diagram of flow around a depression with l = 9.8 mm and h = 3 mm, constructed on the basis of one of the schlieren photographs.

Fig. 2. Diagram of flow around a single depression (h = 3 mm, l = 9.8 mm).

The given spark schlieren photographs reveal evident dependence of frequency of acoustic emission on dimensions of the depression.

Making an analogy with passage through a flow of ultrasonic bundles from ultrasonic emitters and considering that the waves of disturbance fixed on photographs propagate with the speed of sound, it is possible with help of measurements and simple conversions to find wavelengths λ and corresponding frequencies of emission ν. In the experiments described the frequency of acoustic emission thus calculated for rectangular depressions with various values of l and h varied from 15 to 123 kHz. Figure 3 gives the function $\nu = \nu(l)$, and Fig. 4 the function $\lambda = \lambda(l)$.

The graph obtained in Fig. 4 shows that length of emitted



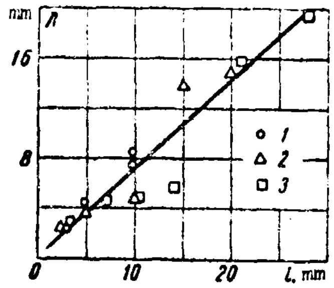


Fig. 3. Fig. 4.

Fig. 3. Dependence of frequency emission on length of depression. 1 — h = 3 mm, 2 — h = 5 mm, 3 — h = 7 mm, 4 — ν = 0.8 u/l.

Fig. 4. Dependence of wavelength on length of depression. 1 — h = 3 mm, 2 — h = 5 mm, 3 — h = 7 mm.

waves in the first approximation is directly proportional to length of depression and does not depend on its depth. This permits making, apparently, only an external analogy with Strouhal sound and describing the dependence of frequency of oscillations on length of depression (taken as characteristic dimension) by the Strouhal formula

$$\nu = K\frac{u}{l}$$

where u is approach stream velocity (in our case u = 530 m/s). In contrast to the Strouhal coefficient, having value K ≈ 0.2 [2], in the examined case dependence $\nu = \nu(l)$ is best approximated by a curve with coefficient K ≈ 0.8, which can be seen in Fig. 3. It is obvious, however, that the obtained formula is valid only under conditions occurring in the experiments described and that without further check with different values of u and different states of the boundary layer it cannot be used.

3. <u>Single depressions of different forms</u>. Figures 1.9-1.16 depict photographs of flow around single depressions of diverse form. The models used here, with the exception of cases stipulated in the text, had vertical dimension h = 5 mm and distance L = 30 mm.

Figures 1.9 and 1.10 gives photographs of flow around a depression with vertical dimension h = 3 mm with cut trailing edge. Distance from the edge of the plate to the leading edge of the depression equaled here L = 15 mm. Photograph 1.9 was obtained with prolonged exposure, and 1.10 with a spark. Photographs show that the presence of cut on trailing edge did not introduce essential change in the character of the flow.

Figure 1.11 shows a spark photograph of flow around a triangular depression. As can be seen, with flow around this depression there is registered neither acoustic emission nor periodicity in the structure of the boundary layer.

Figures 1.12 and 1.13 show spark photographs of an oblique-angled depression with a straight leading edge. Here the ultrasonic bundle is hardly noticed, but periodicity of boundary layer is distinctly expressed.

Figures 1.14 and 1.15 show a depression with a straight trailing edge. The ultrasonic bundle is very clear. Periodicity in structure of boundary layer after the depression is also fairly clearly seen. (The step downwards along flow in our opinion, does not render influence on the examined phenomenon.)

And, finally, the spark photograph (Fig. 1.16) shows flow around a smooth depression (h = 6 mm). Here both acoustic emission and periodicity of boundary layer after the depression are absent.

Common to all the given pictures of flow is strong blurring and an increase in thickness of boundary layer after depressions, which allows saying that in our case all depressions were rather powerful agitators.

4. <u>Consecutive depressions.</u> Figures 1.17-1.24 depict photographs of flow around consecutive depressions of various configurations. Spark photos in Figs. 1.17 and 1.18 show flow around three consecutive depressions with dimensions $h = l = 5$ mm. (The darkening

in the third depression is the shadow of one of the parts bracing the model outside the working part. The same thing occurs in certain other photographs.) It is possible to see that both the first and the second depressions are sources of ultrasonic emission, whereas above the last depression no acoustic bundle is observed. The ultrasonic bundle departs from the first depression in a band approximately equal to the width of the notch. The bundle from the second one occupies somewhat more than half of the width. No satisfactory explanation for this has yet been found.

Figures 1.19 and 1.20 show instantaneous streamline flows of three consecutive rectangular depressions with large dimension l. Here less distinctly than in the preceding case are seen slanted acoustic waves above the first depression. Above subsequent ones such waves are only weakly outlined. These photographs show a sharp increase in thickness of boundary layer and its strong agitation.

The following spark photograph (Fig. 1.21) shows flow around consecutive triangular depressions. Here, in the case of the single depression of similar form, there are seen slanted acoustic waves forming a rather complex picture. It is possible to assume that in this case oscillations are the result of a certain coordination between consecutive depressions.

Figure 1.22 gives an ordinary photo and Fig. 1.23 gives a spark photograph of flow around oblique depressions with straight leading edges. Just as for a single depression of similar form, from the obtained photographs it is impossible to form a definite opinion about the presence or absence of acoustic emission. On these photographs one may see a sharp increase in thickness of boundary layer.

The last spark photograph (Fig. 1.24) shows flow around three consecutive smooth depressions (h = 5 mm). Judging by this photograph, in this case there was no acoustic emission.

Common to all obtained pictures of flow around consecutive depressions is a sharp, noticeably stepped increase in thickness of boundary layer (zone of mixing).

To establish how acoustic emission is affected by a change in the thickness and state of the boundary layer there were conducted a number of experiments with two-dimensional models having a single rectangular depression. The models differed one from another only with respect to the value of L. The range of dimensions L covered both the region of the laminar boundary layer and the region of the transition boundary layer. Spark photographs of all models showed the presence of acoustic emission. In the case of laminar boundary layer the bundle and its individual waves are very clear, while in the transition state of the boundary layer the picture becomes less clear and its individual parts become blurred. The question of whether this is the result of agitation of the boundary layer or the result of only growth of its thickness can serve as the subject of a separate investigation. In any case, the mechanism of damping of emission both in this case and in the case of a number of consecutive depressions seems analogous to us.

5. Discussion of results. As already noted above, in the obtained photographs there are seen bends of border between external flow and volume of air in depression (zone of mixing) and slanted waves of compression and rarefaction going out from these bends, generating in turn an acoustic ray. These bends and slant of waves of disturbance permit assuming that bends of the zone of mixing, crossing at high speed from the trailing edge to the leading edge of the depression, are also sources sending disturbances into the flow. Furthermore, on certain photographs of depressions with comparatively high l there are seen distortions of acoustic waves forming bundles, which can be the result of variable speed of bends of zone of mixing. Thus, the ultrasonic bundle is the result of appearance on the interface of traveling waves. The causes of their appearance can be: a) vortexes stripped from trailing edge of depression; b) instability of boundary; c) excitation of volume of air in depression, similar to excitation of acoustic resonator.

Circulation inside depression, the existence of which is experimentally confirmed [3], is relatively slow and has no significance for the phenomenon of interest to us here.

Photographs show that the boundary layer behind the depression in the defined interval of values of l (in our case l = 1.6-10 mm) has a periodic structure: from the trailing edge, immediately from its whole width, there are broken off vortex lines forming a unique vortex path externally similar to the path discovered by Webb and Harrington [4], who studied the dynamic properties of vortex systems in a flow of water in a pipe with various obstacles on the wall. The scale of vortexes observed by us was approximately proportional to l; however, no clear dependence on l was obtained, i.e., the same l in separate cases corresponded to vortex lines of different scale (see, for example, Figs. 1.2 and 1.3). This permits assuming that appearance of vortex lines is a side phenomenon not determining mechanism of excitation of oscillations. A confirmation of this is the fact that in spite of the presence of ultrasonic emission with $l > 1$ mm (up to $l \approx 30$ mm; further increase in l is hindered by the miniature dimensions of the working part), the periodic structure of the boundary layer behind the depression is already absent here (Figs. 1.7 and 1.8). Thus, the periodicity of structure of boundary layer observed by us was similar to periodicity of flow behind badly streamlined bodies in a certain range of values of the number R [5].

We will examine two other possible causes of formation of traveling waves on the surface of an interface.

By elementary reasonings it is possible qualitatively to show that as soon as an interface (transverse jump of speeds) exists on this surface, with the least deviation of it from the flat form, will there be formed waves progressing along their dimensions, i.e., in general an unstable configuration will be formed (see, for example [6]). Certain given photographs (Fig. 1.3) show these oscillations of zone of mixing to be similar in some cases to a flag waving in the wind. However, on certain photographs (Figs. 1.4

and 1.8) the interface does not have a smooth form, but forms an arc with sharp bends directed in some cases upwards and in other cases downwards.

On the basis of the same photographs it is possible to say that there is participation in oscillations of part of the volume of air in the depression (photographs fixed in depressions the presence of gradients of density). This is confirmed also by experiments with depressions of diverse form.

It is necessary, however, to say that in spite of the fact that "...wind can lead to excitation of cavities" [7], this is not always the case. Thus, in the quoted work the resonator, constituting a tetrahedral pipe closed from one end and set with its mouth perpendicular to the flow, was not excited. In our case, comparing length of cavity with length of emitted waves (Fig. 4), we have longitudinal oscillations of air column with the frequency the 2nd overtone.

In summation it can be concluded that appearance on the interface (zone of mixing) of traveling waves is the result of the appearance of natural oscillations of the system consisting of the interface and the volume of air in the depression.

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