Sound Source Localisation with Acoustic Mirrors

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1 Summary

Acoustic mirrors, also known as sound mirrors, have been used for sound source detection and localisation for many years even though they were not very common. Probably their first application took place on the military field as early warning systems for adversary aircraft. In recent years many of them have been used for sound source determination in rail and road transport. Especially in aeroacoustic wind tunnels sound mirrors have become one of the preferred measurement techniques for the investigation of exterior sound radiation of vehicles and planes. One of their favourable properties is the simple setup which allows easy identification and estimation of the main sources without requiring extensive data processing. On the other hand a complete documentation of the radiated sound pattern may be quite time-consuming.

2 Functional principle and configuration of acoustic mirrors

Acoustic mirrors consist of a paraboloid or ellipsoid mirror body with a microphone positioned at the focal point which records the sound reflected by the mirror surface. In case of paraboloid mirrors beams entering parallel to the mirror axis are registered (see **fig. 1**); in the case of ellipsoid mirrors those beams are registered which emanate from the second focal point of the ellipsoid on the mirror axis (see **fig. 2**).

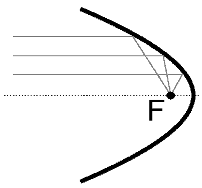

Fig. 1: Function scheme of a paraboloid acoustic mirror [1]

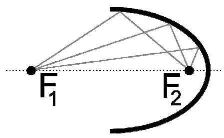

Fig. 2: Function scheme of an ellipsoid acoustic mirror [1]

Owing to their use in communication technology paraboloid mirrors are more easily available than ellipsoid mirrors which normally must be custom-built. Consequently, paraboloid mirrors are used most in the development of acoustic mirrors today. Their slightly poorer spatial resolution can in part be headed off by an ellipsoid-oriented positioning of the microphone.

This requires first of all a precise determination of the shape of the selected mirror and the coefficient m in the mathematical equation of the underlying parabola

$$y = m \cdot x^2 .$$

The ideal microphone position (B) for a required measurement distance (position of the second focal point Q) can be determined according to **fig. 3** by the equation

$$b = mx^2 + x\tan(\pi - 2\arctan 2mx - \arctan\frac{a - mx^2}{x}) .$$

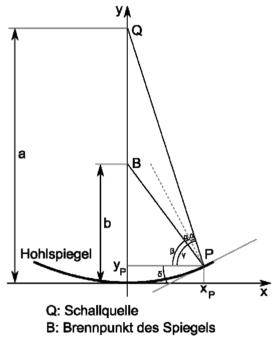

Fig. 3: Determination of microphone position in the acoustic mirror for a certain measuring distance, acc. to [1]

As the equation shows, the result depends on the point of reflection on the mirror (x). Hence no single-valued result can be indicated for the microphone position. Due to the fact, however, that the number of reflected beams increases linearly with the distance from the mirror centre (x=0), determination of the optimal microphone position can be carried out by linear weighting of the calculated results over the parameter x. In this way a characteristic curve can be determined. It represents the relationship between the optimal distance of the microphone and the distance of the noise source from the apex of the parabolic mirror. An example is shown in **fig. 4**.

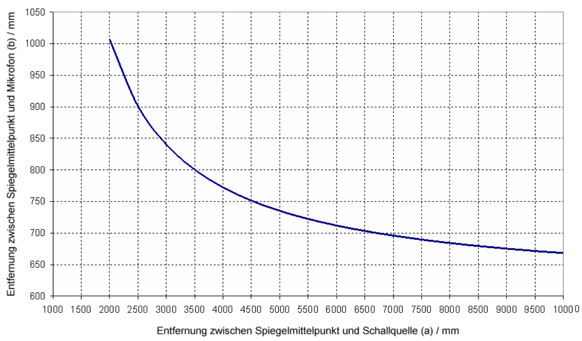

Fig. 4: Relationship between measuring distance and microphone position (example) [1]

3 Historical background

Devices for amplifying and localising sound based on the principle of reflection have been known for centuries. As early as in the 2nd century the Roman doctor Archigenes mentioned an ear trumpet against hardness of hearing and a miniature from the 12th century shows King Arthur hunting with an ear trumpet, which probably served to detect sound sources. The first person to describe this instrument was Athanasius Kircher in 1650, who is thus considered its inventor. In the 18th and 19th century ear trumpets existed in a variety of designs. Some of them were even integrated into furniture (armchairs). The last ear trumpet manufacturer, F. C. Rein & Son in London, shut down in 1963.

The first technical applications go back to the 19th century. The most famous of them is probably the 'topophone' of the American scientist Professor Alfred M. Mayer (1836-1897). Presented in 1880, this consisted essentially of two adjustable hearing cones. By regulating the distance of these cones from each other and their spatial orientation it was possible for sailors to identify the position of other ships' fog horns around them (see **fig. 5**).

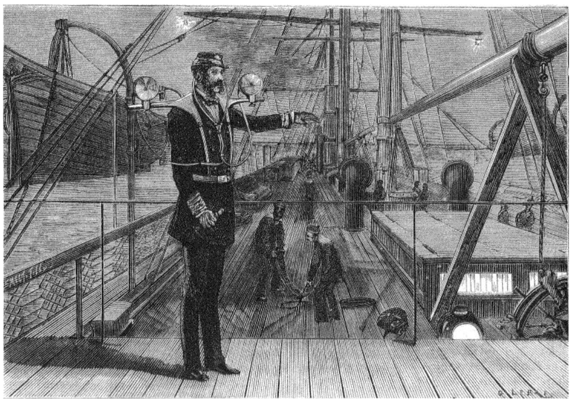

Fig. 5: Application of Alfred M. Mayer's 'topophone' [2]

In the 20th century other systems were used for military purposes. One example is the sound locator of the German Armed Forces shown in **fig. 6**, which was used to localise enemy aircraft. Also the first real acoustic mirrors were developed as early warning systems for the detection of enemy airships or planes. They were set up in the years from about 1915 to 1930 along the south and east coast of England, consisting of a concave-shaped concrete body with an integrated listening device. Frequently this device consisted of a receiving funnel positioned at the focal point of the mirror. The sound was forwarded by means of pipes to a shelter nearby where it was monitored. Some applications also already used microphones.

Fig. 6: Sound locator ('Ringrichtungshörer RRH' of the German Armed Forces (photo courtesy of Helge Fykse)

Several of these concave mirror systems still exist and can be visited. As an example **fig. 7** shows the mirror on the headland of Dungeness (county of Kent) which was probably already equipped with a microphone.

Fig. 7: Acoustic mirror with a diameter of about 9 m on the headland of Dungeness in Kent (photo courtesy of Andrew Grantham)

In vehicle acoustics acoustic mirrors are nowadays mostly used for localising noise when measurements in proximity of the vehicle are too complicated or impossible. They are particularly well suited for use in aeroacoustic wind tunnels with an open-jet test section for determination of exterior aerodynamic noise [1] (see **fig. 8**). For higher effectiveness these systems are often equipped with an additional video camera for observation of the measurement area and a positioning laser for precise adjustment of the device.

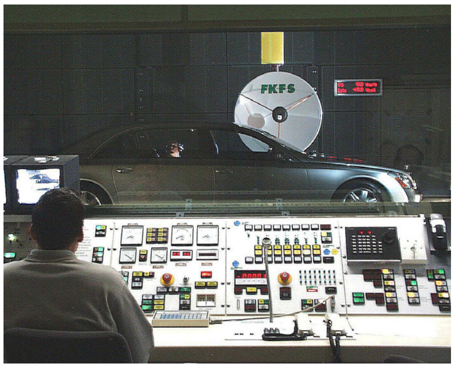

Fig. 8: Acoustic mirror in an aeroacoustic wind tunnel

4 Properties

Just like microphone arrays, acoustic mirrors have certain localisation and signal amplification properties. These depend on the distance from the test object as well as on the size and set-up of the measuring system. The larger the mirror diameter and the smaller the measuring distance, the more precise is in general the spatial resolution of the acoustic mirror. Moreover, the frequency of the measuring signal also plays an important role. Here, higher frequencies are advantageous for both the spatial resolution and signal amplification.

For a point source with a certain frequency the acoustic mirror shown on the left in **fig. 9** measures the signal strength shown on the right when it propagates in x-direction. The position of the mimima above and below the major lobe can be determined [3] by the equation

$$\sin\alpha_{min} = 1.22 \cdot \frac{\lambda}{D}$$

and

$$b = A \cdot tan\,\alpha_{min}$$

or respectively

$$b \approx A \cdot 1.22 \cdot \frac{\lambda}{D} \qquad \text{(for b << A).}$$

From this the half-power width of the major lobe (see **fig. 10**) can be estimated by

$$w \approx 1.1 \cdot b \approx 1.3 \cdot A \cdot \frac{\lambda}{D} \qquad [5,6].$$

Fig. 11 shows the half-power lobe widths for a point source over the frequency measured with two different acoustic mirrors. For e.g. 2000 Hz the theoretical estimate would result in a half-power lobe width of approx. 0.45 m. Thus the measured results largely correspond with the theoretical estimates.

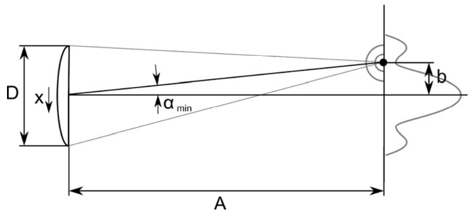

Fig. 9: Schematic diagram for the illustration of the correlation between mirror diameter, measuring distance and precision of localisation (acc. to [4])

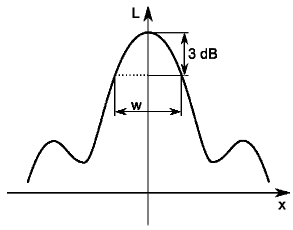

Fig. 10: Definition of the half-power width of the major lobe measured by an acoustic mirror for a point source

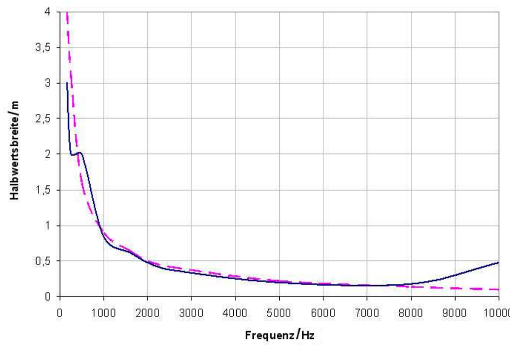

Fig. 11: Half-power lobe width of two acoustic mirrors with different curvatures for a measuring distance A = 4 m and a mirror diameter D of 1.5 m [1]

In contrast to an omnidirectional microphone at the same location, the maximum signal amplification of an acoustic mirror depends on the frequency of the sound signal. The lower frequency range shows the weakest amplification values. Higher amplification in this range can only be achieved by larger mirror diameters. Theoretically, signal amplification increases by 6 dB per octave [4,5]. In the measuring values obtained from two different acoustic mirrors shown in **fig. 12**, however, this value can only be determined approximately as it also depends on the shape of the mirror, particularly the mean curvature radius.

Fig. 14 shows the characteristics of a parabolic acoustic mirror with a diameter of 1.2 m for a point source in the 1 kHz octave. The lower diagram shows the result of a microphone positioning corresponding to a parabolic mirror (Fig. 3: a → ∞), the upper one the result of a microphone adjustment corresponding to an ellipsoid mirror with a measuring distance of 7.5 m. The colour coding shows the sound pressure levels at the microphone for the source locations on the measured surface. It becomes apparent that focusing the ellipsoid mirror has no effect along the longitudinal axis. For both settings the sound pressure drops over the distance to the microphone. Concerning the accuracy of localisation, however, the ellipsoid setting turns out to have some advantages: the width of the main lobe is somewhat narrower and the sound pressure does not drop as much over the distance.

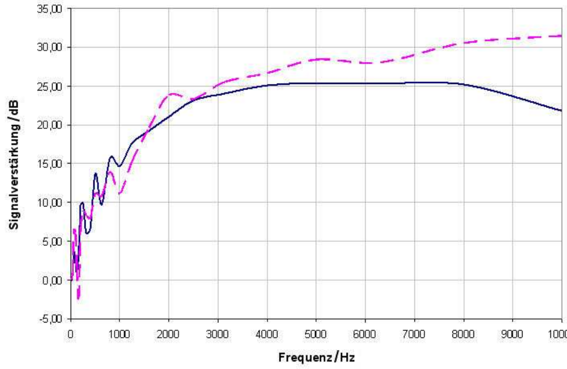

Fig. 12: Amplification of two acoustic mirrors with different curvatures for a measuring distance of A = 4 m and a mirror diameter D of 1.5 m [1]

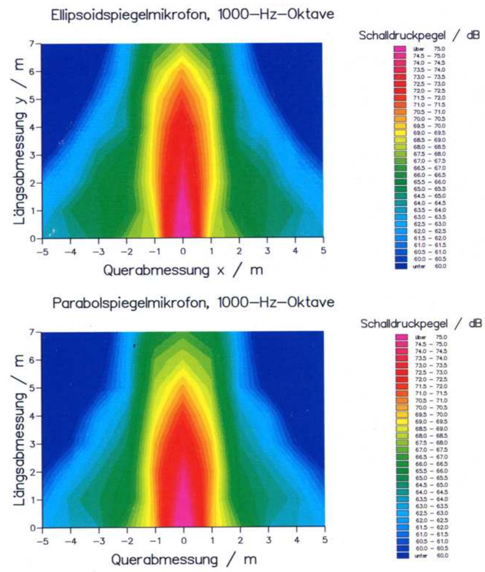

Fig. 13: Directivity of differently designed acoustic mirrors (microphone position: above: ellipsoid, below: parabolic); diameter D = 1.2 m) [8][1]

[1] 0 m „Längsabmessung" corresponds to a distance of 3.5 m from the microphone; focus for the ellipsoid setup: 4 m "Längsabmessung" (thus 7.5 m from the microphone)

5 Special designs

For special applications array-based acoustic mirrors prooved to be efficient in the recent years [1,7]. In these mirrors a number of closely spaced microphones (instead of just one) are positioned on a plane vertical to the mirror axis. As illustrated in **fig. 14**, each of these microphones is positioned at a special focal point corresponding to an 'own' ellipsoid, of which the mirror constitutes a partial section. So, each of the microphones focuses, via this focal point, on its own measurement point on the test object (the second focus of the respective ellipsoid). This permits the simultaneous measurement of the radiation pattern of an entire surface without any need of traversing the acoustic mirror. **Fig. 15** shows the application of such a system in an aeroacoustic wind tunnel.

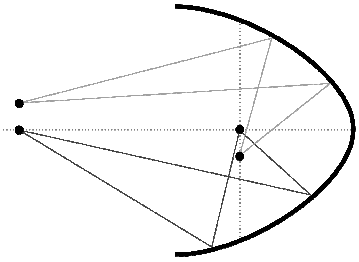

Fig. 14: Function scheme of an array-based acoustic mirror

Fig. 15: Application of an array-based acoustic mirror in an aeroacoustic wind tunnel (photo courtesy of Daimler AG)

6 Examples of use

Acoustic mirrors are primarily used in wind tunnels with open-jet test section. The first objects to be tested came from aerospace research [4,5]. Later, also investigations on rail vehicles (e.g. pantographs [7]) and road vehicles were carried out [1]. As an example **fig. 16** shows the aerodynamic sound source distribution of a vehicle in a wind tunnel. However, acoustic mirrors have also been used for in situ measurements of traffic noise. Some of the array-based versions, for example, have prooved to be very effective to localise noise sources of passing trains [6].

Acoustic mirrors can also be used to advantage when it is not necessary to record the overall sound source distribution. For example, individual vehicle sections can already be acoustically optimised in wind tunnels, when it is not yet possible to carry out interior sound measurements (e.g. in the model phase). The a-pillars or windshield wipers, for example, can be acoustically assessed by carrying out measurements with an acoustic mirror positioned above the vehicle measuring only two to three radiation points on the appropriate device in each case.

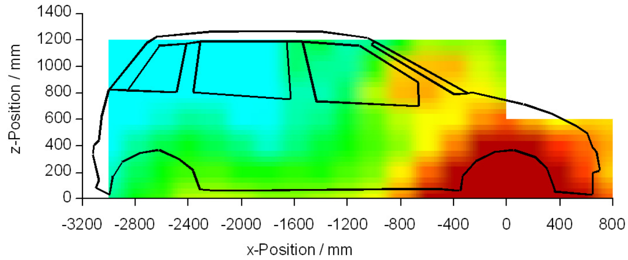

Fig. 16: Sound radiation pattern of a vehicle in an aero-acoustic wind tunnel for the 2.5 kHz third octave band [1]

5 References

[1] Helfer, M.: Hohlspiegelmikrofone. Workshop 'Mess- und Analysetechnik in der Fahrzeugakustik', 09.-10.10.2007, at FKFS in Stuttgart

[2] N.N.: Appareil acoustique pour reconnaître en mer le lieu de production d'un son. La Nature, no. 391, 27.11.1880, p. 401

[3] Sommerfeld, A.: Vorlesungen über theoretische Physik - Bd. IV: Optik. Frankfurt: Harry Deutsch Verlag, 1989, ISBN 978-3871443770

[4] Grosche, F.-R.; Stiewitt, H.; Binder, B.: Sound Source Location and Discrimination from Background Noise in Wind-Tunnel Tests. International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF'75), Ottawa (CDN), 22.-24.09.1975

[5] Grosche, F.-R.; Jones, J. H.; Wilhold, G. A.: Measurement of the Distribution of Sound Source Intensities in Turbulent Jets. In: Duct Acoustics (Progress in Astronautics and Aeronautics, Vol. 37, AIAA, 1975), pp. 79-92

[6] Grosche, F.-R.: Application Possibilities of Acoustic Mirrors for Noise Source Localization. DGLR Workshop on the Aeroacoustics of Cars, 16.-17.11.1992 at DNW in Noordoostpolder, The Netherlands

[7] Grosche, F.-R.: Source Location and Investigation of Aerodynamic Sound Sources by the Elliptic-Mirror-Microphone System in the DNW and other Wind Tunnels. First CEAS-ASC Workshop on Wind Tunnel Testing in Aeroacoustics, 05-06.11.1997 at DNW in Noordoostpolder, The Netherlands

[8] Helfer, M.: Beurteilung von Hohlspiegelmikrofonen zur Schallquellenortung. In: Ahmed, S. R.: Akustik und Aerodynamik des Kraftfahrzeugs. Renningen: Expert-Verlag, 1994. ISBN 3-8169-1190-0