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Sound Amplification by a Supersonic Jet

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Introduction

THE possibility of amplifying sound waves incident on a shear layer is indicated in Ref. 1. This numerical–analytical work shows that, at certain angles of incidence, for the sound wave on an infinite linearly stabilized shear layer with a relative Mach number $M > 2\sqrt{2}$, the amplitude of the reflected waves is much greater than the incident wave amplitude. It is noted in Ref. 2 that in the case of sound excitation of a supersonic jet shear layer (at $M < 2\sqrt{2}$) the intensity of sound waves radiated by such a jet at the external excitation frequency can also exceed the intensity of the incident sound wave. Despite an apparent similarity of these phenomena, the essential distinction is that in the first case a reflected wave is considered. Its reflection angle depends on the sound incidence angle to the shear layer. In the second case, the sound radiation by a supersonic jet at the external excitation frequency occurs in a direction independent of the sound incidence angle. This relates to the radiation of Mach waves by disturbances arising in the shear layer under the action of sound and moving with a supersonic convective velocity along the jet boundary.[3] In this work it is also shown that the amplitude of disturbances arising in the supersonic jet at the nozzle exit depends on the sound incidence angle to the jet boundary. The most intensive disturbances arise in the jet for oblique sound incidence to the jet boundary. It is possible to expect that the intensity of sound waves radiated by the supersonic jet at the external excitation frequency also depends on the sound incidence angle to the jet boundary. In the present work the possibility of sound amplification of a sawtooth-like sound wave incident on the supersonic jet boundary is considered.

Results and Discussion

The investigations were carried out in an anechoic chamber of the Acoustic Division of the Central Aerohydrodynamic Institute with an isothermal supersonic air jet issuing from a conical supersonic nozzle designed for $M = 2.0$ with an exit diameter $d = 20$ mm. The total pressure P_0 in the settling chamber of the nozzle varied from 3.9 to 15.6 atm. A Hartman generator (HG) was used as the sound source ($f = 10$ kHz; Fig. 1). Its central core moved along an arc of 100-mm radius, with its center on the nozzle lip nearest to the sound generator. The angle β between the jet flow direction and the direction to the sound source varied from 90 to 140 deg.

Acoustic measurements (rms value of the sound pressure) were carried out with a Bruel and Kjaer microphone, Model 4136, moving along an arc of 40-mm radius with its center on the nearest nozzle lip, as shown in Fig. 1. The angle between the jet flow direction and the direction on the microphone varied from 20 to 35 deg. Analysis of the data obtained was made with a Bruel and Kjaer spectrometer, Model 2034, where the accuracy of the data obtained is ±1 dB. The location of the measurement point was chosen to approach the radiation source in the jet as closely as possible and, on the other hand, to keep the microphone out of the hydrodynamic near field of the supersonic jet. To remove the influence of high pressure fluctuation levels generated in the near field of supersonic jets, all of the measurements were performed at the fundamental frequency of the HG. In the experiments, the sound pressure level (SPL) on the nozzle lip at the fundamental frequency was 146–148 dB. The SPL produced by the undisturbed jet and the HG at the measurement points at the fundamental generator frequency varied from 125 to 135 dB, according to the jet issuing regime and the measurement point position. Visualization of flow and sound waves was carried out with a direct shadowgraph technique using a spark source. (The size of the luminous body was 0.8 mm, and the exposure time was 2×10^{-7} s.)

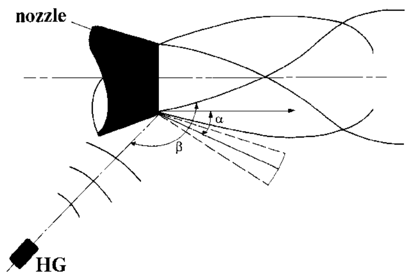

Fig. 1 Scheme of the experiments.

A typical shadowgraph, indicating the main features of the phenomenon under consideration, is presented in Fig. 2, which shows an incident sawtooth-like sound wave, disturbances in the jet formed under acoustic excitation, and Mach waves. (The incident sound wave propagation direction and the Mach waves radiation direction are indicated by arrows.)

The directionality of the radiated sound on an arc of 40-mm radius ($\beta = 130$ deg) shows that, under the action of sawtooth-like sound waves of sufficiently high intensity, the sound amplification does occur (Fig. 3). The intensity of sound radiated by the jet at the fundamental frequency (for HG and jet parameter values under investigation) can exceed the intensity of sound in the incident wave at the nozzle lip by up to 20 dB. At subcritical values of the jet total pressure, the convective velocity of the disturbances is less than the sound speed, Mach wave radiation is absent, and the sound intensity at the measurement points corresponds to the SPL in the incident wave (curve 5 in Fig. 3).

The most significant sound amplification is observed at oblique sound incidence to the jet boundary at the highest values of the jet total pressure investigated. If the sound incidence angle to the jet decreases, the intensity of sound radiated by it, as a rule, decreases. Thus, the influence of the jet total pressure on the intensity of sound radiated by the jet also decreases, but the tendency remains that under other constant conditions the jet with the higher total pressure value radiates the sound of higher intensity.

It seems evident that the possibility of sound amplification of a sawtooth-like sound wave incidence on the supersonic jet boundary is associated with the appearance and propagation of reasonably intensive disturbances, along the jet boundary, that are accompanied by Mach wave radiation. As the tests conducted have shown, the greater their intensity at the constant sound wave angle of incidence to the jet, the more the SPL is in the incident wave. Increasing the Mach wave intensity at sliding angles of incidence to the jet, in comparison with the case of normal sound incidence at constant values of SPL on the nozzle lip, is evidently connected with an increase in the amplitude of the disturbances. As a possible reason for this increase in the disturbance amplitude, it was suggested that there was a possibility of sound wave energy transfer to the vortex motion when the disturbances displaced the jet boundary.[3] However, it was noted that such treatment was not the only one possible. Another possibility is that the interaction of a sawtooth-like sound wave of a finite amplitude with a supersonic jet occurs in an extremely small time and space interval. It occurs when the zone of the maximum sound wave compression phase passes through the nozzle exit and is localized close to the nozzle edge. In this case, the sound incidence angle influence can consist of producing certain favorable ratios between the velocity of spreading the maximum compression phase in the incident sound wave over the nozzle edge and the phase speed of the vortex separation location shift from the nozzle lip. Evidently,

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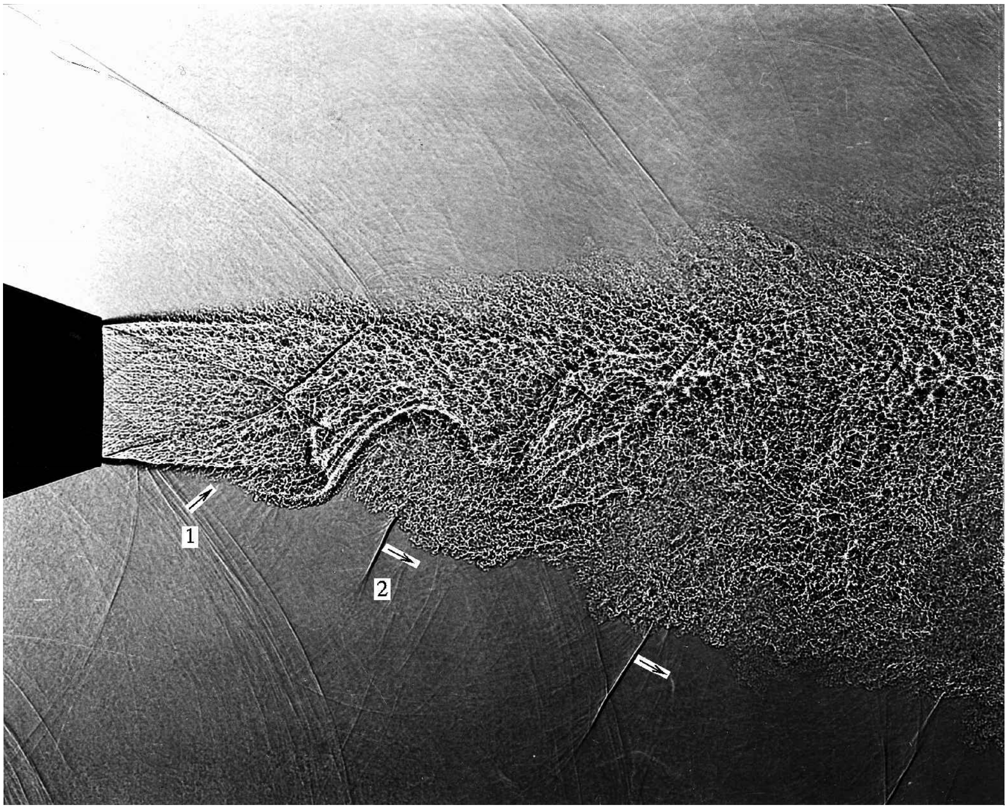

Fig. 2 Supersonic jet shadowgraph of the sound wave incidence to the jet boundary, β = 130 deg and P_0 = 6.2 atm: 1, incident wave, and 2, Mach wave.

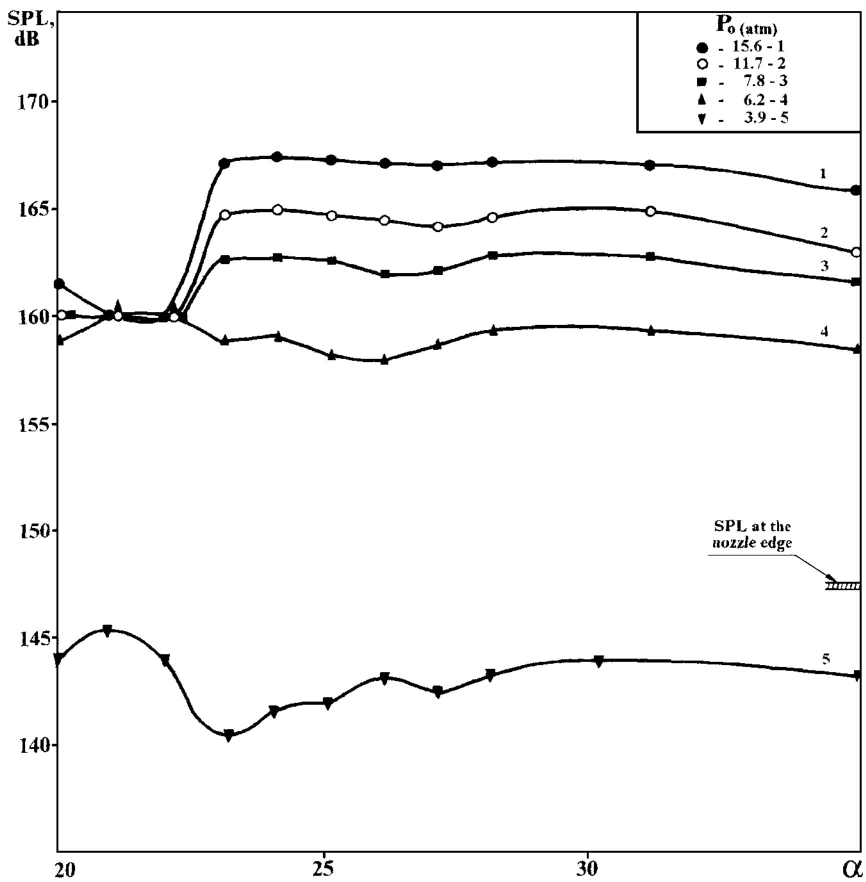

Fig. 3 Distribution of the SPL in the sector of angles of 20–35 deg under the action of a sawtooth-like sound wave of a finite amplitude on the supersonic jet, β = 130 deg and P_0 = 6.2 atm.

a certain influence on the intensity of disturbances formed in the supersonic jet under sound excitation is a result of the relation between the oscillating velocity vector direction in the incident sound wave and the jet issue velocity direction.

Conclusion

Thus, at certain incidence angles of the sawtooth-like sound waves of a finite amplitude to the linearly unstable shear layer of a supersonic jet, a significant amplification of sound radiated by such a jet at the external excitation frequency is possible. This radiation is connected with the intensity increase of disturbances generated in the jet under sound excitation and, as a consequence, with the intensity increase of Mach waves radiated by them.

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Numerical Stability Conditions in the Calculation of Potential Velocity Fields

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Introduction

IN recent years, the development of numerical calculation has lead to reductions in calculation times and costs and has enabled a deeper understanding of the flow structure through turbomachinery and physical processes that govern the internal phenomena.

The singularities method is used to analyze the flow through turbomachinery.[1–5] This method enables particular solution of the Laplace equation, which satisfies the imposed boundary conditions. The method is very useful because it allows one, once the calculation programs are ready, to study the flows by the superposition of the following elementary flows[6–8]: a basic uniform flow and sources, sinks, or vortices located at well-chosen points in the flowfield. The aim of this study is to highlight the problems met during the numerical programming of the method and also to propose, in many cases, a solution. A large part of this work is based on the Joukowski profiles for which the analytical solution of the flow is known.[9] We adopt the following nomenclature to define these profiles: Jouko 04 80 10, where Jouko is the Joukowski profile, 04 is the absolute value of the camber angle β (deg), 80 is the [1 − relative thickness] × 100 ($e = 20\%$), and 10 is the angle of attack α_0 (deg).

The Joukowski profile, with its fine or cusped trailing edge, presents the most difficulties for application of the Kutta condition and, consequently, for numerical stability. This profile is presented as an ideal means to validate a potential calculation code. A numerical study has been developed to discuss the accuracy of the solutions. The aims of this study are summarized as follows:

1) Provide an accurate solution for these different problems. For example, some profiles, obtained by the Joukowski transformation present, in spite of an analytical definition, a crossing of the suction and pressure sides at the trailing edge. This crossing causes a serious error in the velocity field computation. A new procedure to solve this problem is presented.

2) Expose the elements that influence the method: precision in the geometrical profile definition, trailing-edge geometry, smoothing problems, number of discretization points, precision of calculation, etc.

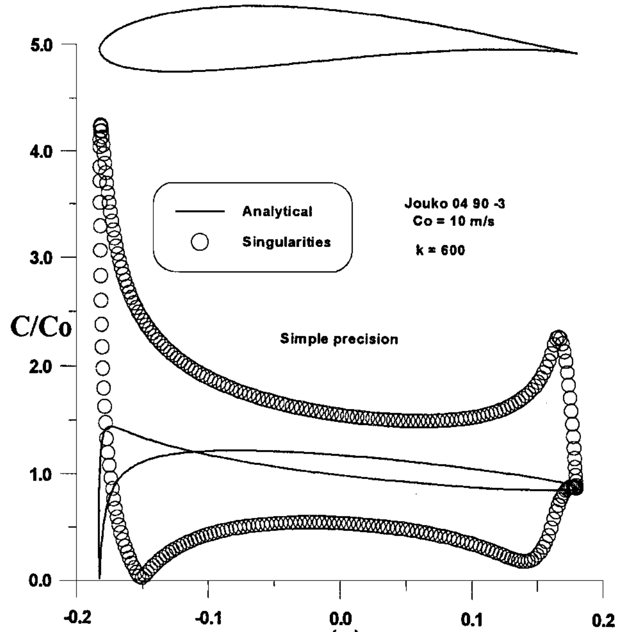

Fig. 1a Simple precision.

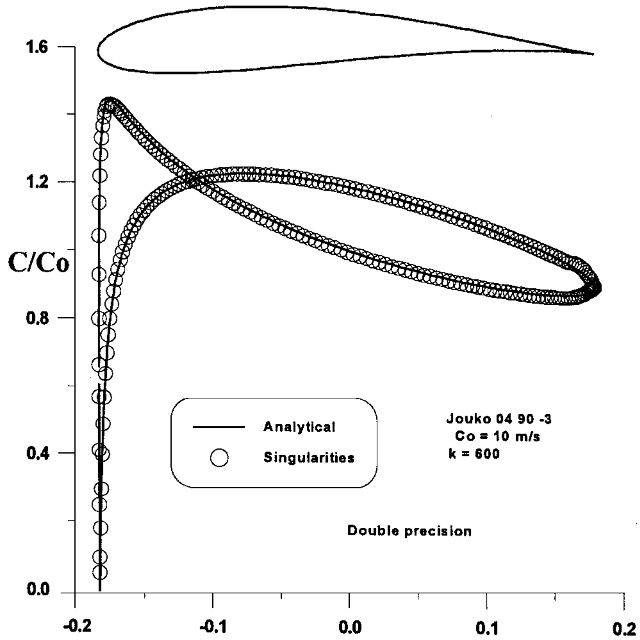

Fig. 1b Double precision.

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