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Finite-amplitude and diffusive effects in acoustics: a report on EUROMECH 23

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The 23rd EUROMECH colloquium on finite-amplitude and diffusive effects in acoustics was held in Rapperswil (Switzerland), 5–7 April 1971. There were 41 participants from 7 countries, and the authors were the chairmen of the meeting organization. References quoted in this report give the titles of the talks and sources for further details of the work described at the meeting; there will be no other publication of the proceedings. The subject matter of this meeting was more strongly restricted than is indicated by its title, inasmuch as papers motivated solely by sonic-boom research problems were not included. Included in particular were problems of acoustic damping by relaxation, dust, moisture, etc.; damping in ducts; effects of turbulence; acoustic streaming; and thermo-acoustic effects.

1. Acoustic damping in general and relaxation effects

The meeting was opened by an invited lecture by Lighthill, who presented an up-to-date version of his basic 1956 paper, emphasizing in particular the means by which the restriction to weak shocks, on which many of the results of the original paper rests, can be relaxed. Becker* gave a simple derivation of an interesting equation which has proved itself useful in the investigation of the problem of formation of shocks in relaxing gases. Schmitt* attacked the same formation problem by using an expansion, valid for times small compared to the relaxation time. A paper by Schmitt-v. Schubert* gave a discussion of sound waves in a dusty gas, including the effects of the velocity and temperature lag between gas and solid particles for the whole possible range of both lag times. Hodgson & Johannesen* solved the problem of a weak fully dispersed wave in the presence of relaxation effects in the atmosphere, with particular application to sonic bangs.

2. Damping in ducts

The damping of acoustic waves in a pipe of arbitrary cross-section, using the boundary layer (i.e. Helmholtz–Kirchhoff) approximation, was given by Peube*. Harel & Perulli* investigated several aspects of the theory of waves in a duct with uniform axial flow and their dependence on the wall impedance. Dean & Tester* discussed the methods of measuring the wall lining impedance in ducts with mean flow, which was shown to be a necessary prerequisite for correct evaluation of the attenuation. Ronneberger* reported on a numerical analysis of waves in a hard-walled duct, with the axial velocity given by the turbulent pipe-flow profile. The calculations were based on the Navier–Stokes equations, with no direct effects of the turbulence taken into consideration. Comparison with experiment indicates that the assumptions were well justified up to a certain critical value of the shear velocity; beyond that value, direct interaction between sound and turbulence possibly exists.

3. Turbulence and acoustic damping

The interaction of waves and turbulence with a perforated solid boundary was the subject of a paper by Ffowcs Williams*, who proposed a model representation of the perforated wall by sources and sinks, driven by the turbulent wall-pressure fluctuations. He also proposed experiments to check the model by the power-law dependence on the velocity of the different components of the wave field. The general problem of defining and separating acoustic, turbulent and thermal components in a compressible turbulent field was attacked by Doak*; his claim that his analysis makes these definitions unambiguous met with some scepticism. The investigation of the interaction of flow gradients with sound propagation was proposed by Mungur* on the basis of small disturbance theory.

4. Non-linear effects

The session on non-linear effects was opened by two papers on acoustic streaming: first, Bertelsen & Tjøtta* considered the classical problem of the oscillating cylinder, albeit with a large coaxial cylinder at rest giving the outer boundary condition, treated earlier theoretically by Svardal. They observe the motion of particles by illuminating them with a stroboscope, synchronized with the motion of the cylinder. Agreement with calculated flow patterns was shown for the low and the high Reynolds number theory, and for a wide range of other pertinent parameters; it was noted that the particle path calculations (not identical with the streamlines of the mean flow component) have to be properly performed. Riley* considered the steady streaming velocity induced by a stirring action due to the circular motion of a circular cylinder. For high frequencies and small amplitudes, he finds a thin Stokes layer and a persistent induced streaming outside this region. Unlike the case of a cylinder performing transverse oscillations, the equation for the persistent streaming outside the Stokes layer in this problem involves the Reynolds stresses. However, for the particular case of a circular cylinder, the streaming is independent of the streaming Reynolds number. The author verified his results with simple experiments, noting the long time which elapses before the analytically described flow is established.

The inviscid standing wave solution in a tube provided the first approximation for a second-order calculation of Chasseriaux*, who calculated in particular the change of mean pressure in the tube by use of the quadratic terms and compared the results with experiments. The existence of the well-known Rayleigh theory, which takes the viscous (Kirchhoff) solution as a first approximation, was noted in the discussion, but apparently for the calculation of the mean pressure change alone it is not needed. Jessel* investigated the usefulness of several definitions of the 'radiation tensor' in non-linear acoustics in particular one based on a proposal by Brillouin (1956). An interesting series of observations was described by Schaaffs*: if a beam of ultrasonic waves is sent into a fluid in which some substance is in solution, and the concentration of the solution has a gradient in the direction of the wave propagation, then a periodic density stratification, whose scale is the half-wavelength, is formed in the fluid. Schaaffs showed several examples of such concentration patterns (which have a long persistence after the ultrasonic source has stopped) by means of optical visualization. This effect (found in all sorts of solvents and solutions) strongly suggests some kind of acoustic streaming for its explanation, but there are indications in the vorticity pattern that it is not the Rayleigh type acoustic streaming that is responsible for these effects. According to an explanation offered on the spot by Tjøtta, an acoustic streaming connected with the damping *along* the wave, which only becomes important for extremely high frequencies, leads to a convection pattern that explains the observations of Schaaffs.

5. Thermo-acoustic effects

The paper presented by Rott* dealt with the spontaneous oscillations observed in ducts of cryogenic helium gas. The author had previously shown (1969) that the failure of a calculation of the stability limit by Kramers (1949) is due to a 'quirk of nature'. Kramers generalized the Kirchhoff theory to variable wall temperature using a boundary layer approximation, and this approximation fails as the coefficient of a crucial function vanishes, as it happens to do when the material constants of helium are inserted. With an approximation which does not use the assumption of Stokes layers thin compared to the radius, but takes the acoustic pressure constant across the tube, a differential equation for the pressure along the tube results; its solution (analytically and numerically) has led to stability limits in good agreement with experience. If the wall temperature is taken to be discontinuous at one point of the tube, the effect of this on the oscillations can be shown to be equivalent to a periodic heat source, and Rayleigh's explanation for thermally driven oscillations (in connexion with the Rijke tube) can be applied.

The thermal effects connected with the Hartmann resonator, discovered earlier by Sprenger*, were demonstrated by the discoverer at the meeting. Brocher & Maresca* presented two papers on the explanation of the phenomenon observed in those 'resonance tubes', which made it clear that the name of this device is highly misleading; as an outgrowth of suggestions made at the meeting, it is proposed now to speak of a 'Hartmann–Sprenger' (or HS) tube. In the first paper, the authors established the answer to two crucial questions which occur in connexion with the explanation of the HS-tube: (1) what is the steady-state mode of operation of the tube, and (2) how can this steady state be reached? The answer to (1) is that in the steady state, the pressure in the tube, at the moment when the jet begins to move into the tube at the open end, is essentially equal to the jet static (i.e. atmospheric) pressure. Thus the jet is fully swallowed, and a cycle is formed whose frequency and amplitude can be calculated from the well-known methods of gas dynamics. The authors find excellent agreement between theory and experiment for jet Mach numbers from 0·1 to 2. Then, the question has to be answered how the steady state is reached, because initially the pressure in the tube, when the jet hits, is about equal to the jet stagnation pressure: thus, the tube has to be 'emptied' until a pressure reduction by the amount of the jet dynamic pressure has been achieved in the tube. The authors have shown that this emptying occurs whenever the jet stagnation pressure has a 'dip' around the jet axis; such total head defects were produced by placing a thin, wake-producing cylinder along the jet axis. In the second paper, the authors attacked the difficult problem of the heat balance in the HS-tube. The most important mechanism that limits the temperature increase is found to be in the mass exchange between hot (tube) and cold (jet) gas. This exchange takes place through the boundary layer at the contact surface. The authors have already obtained reasonable agreement with observations of the wall temperature, by use of this model, for the region of the tube from the open end to the point of deepest penetration of the jet interface (which lies for high jet Mach numbers rather close to the closed end of the tube).

In the discussion, the point was emphasized by Ackeret that a total energy balance for the Hartmann–Sprenger (as well as for the possibly related Ranque–Hilsch) tubes involves a cooling effect; its detailed mechanism is still not well understood. An experiment aimed at a total energy balance was described in a brief communication by Merkli*: a wave produced in a tube by the motion of a piston at one end is investigated. Comparing the resulting pressures with the predictions of the viscous linear theory, Merkli finds good agreement in off-resonance points; near resonance, the non-linear effects were clearly predominant for the case under consideration. The purpose of this experiment is to clarify, in the formulation of Thomann, the question of why heating effects are strongest at the velocity nodes, while dissipation has its maxima at the antinodes. A further short communication by Monkewitz* pointed out that the Kirchhoff theory as used in the paper by Rott (1969) leads to a critical Reynolds number for a tube, below which the proper modes become aperiodic. Whitehead*, also in a brief communication, reported on experiments on the excitations of acoustic resonances in a short cylindrical tube using pulsed electric arcs. As the frequency is varied, the resonance curve shows indications of the importance of non-linear effects.

6. Miscellaneous topics

Experiments of Hiller, Jaeschke & Meier* investigated a transonic free jet formed in a Laval nozzle by separation shortly after the throat. They observed that the sound production in a moist air jet, in which condensation products are found, is up to 10 db less than in dry air. In the discussion, possible implications for the jet noise problem were questioned.

A low-density acoustic problem was treated by Fiszdon & Grzedzinski*, who calculated the propagation of acoustic pressure waves generated in a highly rarified gas flow by an oscillating membrane moving with hyperthermal speeds. The authors have shown that the results depend critically on the gas-surface interaction models of the molecular reflexion.

In a short communication, Heckl* has shown that the damping of the bending oscillations of a thin membrane (beyond the internal damping) is due to the Stokes layers formed on the surface in the surrounding medium; it is proportional to the ratio of the mass of the fluid contained in the Stokes layer to the mass of the membrane.

In the final discussion Lighthill emphasized our indebtedness to Rayleigh. It seems indeed that only our frequent need to have a more detailed knowledge of certain phenomena motivates our continuing work beyond Rayleigh's. The problems treated in the colloquium fall certainly into this category; others which were mentioned in discussion are: combustion, noise in jet and rocket engines, where unsteady chemical reactions give rise to strong source terms; generation, absorption and scattering of sound by turbulence; second-order effects in ultrasonics.

REFERENCES

(An asterisk to a name indicates a lecture given at the Symposium.)

AHRENS, C. & RONNEBERGER, D. Luftschalldämpfung in turbulent durchströmten Rohren mit glatten und rauhen Wänden (to be published in *Acustica*).

BECKER, E.* Einfluss der akustischen Dämpfung auf die Entstehung von Unstetigkeiten in fortlaufenden Wellen.

BECKER, E. & SCHMITT, H. 1968 Die Entstehung von ebenen, zylinderund kugel-symmetrischen Verdichtungsstössen in relaxierenden Gasen. *Ing. Archiv* **36**, 335.

BECKER, E. 1970 Die Entstehung von Verdichtungsstössen in kompressiblen Medien. *Ing. Arch.* **39**, 302.

BECKER, E. 1970 Relaxation effects in gas dynamics. *Aeron. J. Roy. Aero. Soc. J.* **74**, 736.

BERTELSEN, A. & TJØTTA, S.* Non-linear streaming effects associated with oscillating cylinders.

BRILLOUIN, L. 1956 Les pressions de radiation et leur aspect tensoriel. *Journal de Physique*, **17**, 379.

BROCHER, E. & MARESCA, CH.* Fluid dynamics of the resonance tube.

BROCHER, E. & MARESCA, CH.* Thermal effects in resonance tubes.

BROCHER, E. & MARESCA, CH. 1971 *J. Fluid Mech.* **43**, 369.

BROCHER, E. & MARESCA, CH. 1970 *Comptes Rendues*, **271**, 737.

CHASSERIAUX, J.* Ondes stationnaires unidimensionelles d'amplitude finie dans un fluide parfait (to be published in *J. Sound Vib.*).

DEAN, P. D. & TESTER, B. J.* The acoustic impedance of resonant-cavity duct liners in the presence of parallel mean flow.

DOAK, P. E.* The nature of the interdependence amongst acoustic tubulent and thermal fluctuations in unsteady fluid flows (to be published in *J. Sound Vib.*).

FFOWCS WILLIAMS, J. E.* The interaction of waves and turbulence with a perforated solid boundary.

Ffowcs Williams, J. E. The acoustics of turbulence near sound absorbent liners (to be published).

Fiszdon, W. & Grzedzinski, J.* The influence of gas-oscillating surface interaction model on distribution of pressure impulse in free-molecular hyperthermal flow (to be published in *Arch. Mech. P.W.N.*, Warsaw).

Harel, P. & Perulli, M.* Theoretical study of the space-time structure of acoustic waves in a duct.

Harel, P. & Perulli, M. 1971 The influence of a stationary uniform axial flow on the propagation of acoustic modes of vibration in a cylindrical duct. *J. Sound Vib.* **14**, 4. See also TPP, ONERA no. 844.

Heckl, M.* Dämpfung von Biegewellen durch die Viskosität des umgebenden Mediums (to be published in *Acustica*).

Hiller, W. J., Jaeschke, M. & Meier, G. E. A.* Einfluss der Luftfeuchtigkeit auf schwache Stosswellen in transsonischen Freistrahlen. (GAMM Sonderheft *Z.A.M.M.* 1970.)

Hodgson, J. P. & Johannesen, N. H.* Real-gas effects in very weak shock waves in the atmosphere and the structure of sonic bangs (to be published).

Jessel, M.* Tensions de radiation et acoustique non lineaire.

Kramers, H. A. 1949 Vibrations of a gas column. *Physica*, **15**, 971.

Lighthill, M. J. 1956 Viscosity effects in sound waves of finite amplitude. In *Surveys in Mechanics* (Cambridge University Press).

Merkli, P.* Versuche mit Resonanzrohren kleiner Amplitude.

Monkewitz, P.* Decay of an acoustic wave system in a cylindrical tube.

Mungur, P.* Sound transmission in subsonic shear flow.

Mungur, P. & Gladwell, G. N. L. 1969 Acoustic wave propagation in a sheared fluid. *J. Sound Vib.* **9**, 28.

Mungur, P. & Plumblee, H. E. 1969 Sound propagation in a soft-walled annular duct with shear flow. *NASA* Basic Noise Research Symposium, Washington.

Peube, J. L.* Propagation des ondes dans une conduite cylindrique de section quelconque.

Peube, J. L. Wave propagation in a quasi-cylindrical duct with an arbitrary variable cross-section (to be published).

Peube, J. L. & Arnaud, G. 1969 *Comptes Rendues*, **268**, 1134.

Riley, N.* Stirring of a viscous fluid (to be published in *Z.A.M.P.*).

Ronneberger, D.* Berechnung der Luftschalldämpfung in luftdurchströmten, harten Rohren (to be published in *Acustica*).

Rott, N.* Thermally driven acoustic oscillations.

Rott, N. 1969 Damped and thermally driven acoustic oscillations in wide and narrow tubes. *Z.A.M.P.* **20**, 230.

Schaaffs, W.* Ueber die Einfrierung des Amplitudengitters einer in einer Diffusionsstrecke erzeugten Ultraschallwelle.

Schaaffs, W. & Haun, L. 1968 Einfrierung stehender Ultraschallwellen mit Hilfe des Konzentrationseffekts. *Acustica*, **20**, 348.

Schaaffs, W. 1968 *Kolloid-zeitschrift & Z. Polymere*, **227**, 131.

Schaaffs, W. & Haun, L. 1970 *Z. Angew. Phys.* **28**, 373.

Schmitt, H.* Formänderung von fortlaufenden Wellen durch thermo-dynamische Relaxation.

Schmitt, H. 1968 Fortpflanzung schwacher Unstetigkeiten bei nichtlinearen Wellenausbreitungsvorgängen. *Z.A.M.M.* **48**, 241.

Schmitt-von Schubert, B.* Schallwellen in Gasen mit festen Teilchen.

Schmitt-von Schubert, B. 1969 Schallwellen in Gasen mit festen Teilchen. *Z.A.M.P.* **20**, 922.

Schmitt-von Schubert, B. 1969 Existence and uniqueness of normal shock waves in gas-particle mixtures. *J. Fluid Mech.* **38**, 633.

Schmitt-von Schubert, B. 1970 Struktur stationärer Verdichtungsstösse in Gasen mit festen Teilchen. *Z.A.M.M.* **50**, 671.

Sprenger, H.* Demonstration von Resonanzrohren.

Sprenger, H. 1954 Ueber thermische Effekte in Resonanzrohren. *Mitt. Inst. Aerodyn. ETH Zürich* no. 21.

Svardal, A. 1965 On acoustical streaming between two coaxial cylinders. *Dept. of Appl. Math. Rep.* no. 7, Univ. of Bergen.

Tester, B. J. & Dean, P. D. 1971 *Inst. Sound Vib. Res., Memo* no. 420.

Whitehead, D. S.* Contribution to discussion on resonance tubes and thermal oscillations.