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Hydroacoustics Research in Europe
Patrick Leehey
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HYDROACOUSTICS RESEARCH IN EUROPE

Hydroacoustics is the low mean flow Mach number portion of the field of aerodynamic sound. Its applications are becoming more and more directed to problems in underwater acoustics. Almost 35 years ago, the advent of the jet engine with its accompanying loud rumbling turbulence noise ushered in an era of research in aeroacoustics. The milestone work by Lighthill in 1952 set the tone for jet noise research for many years to come. This work was accompanied by studies of blade slap noise of helicopters, rocket engine noise, and even aircraft propeller noise.

Jet noise research is continuing. However, the advent of the high-bypass-ratio engine has greatly alleviated the severity of the problems associated with jet engine noise. The attention of most research activities has therefore shifted in other directions, the marine application being one of predominate interest today. For example, the aeroacoustics group at the National Aerospace Research Office (ONERA) in Chatillon, France, is now busily engaged in marine problems. Even its anechoic wind tunnel, originally designed for jet engine noise research, is being used today primarily for the study of problems related, more or less directly, to marine matters. In the past year there have been two European conferences on the subject of hydroacoustics. One was Euromech 188 at Leeds University, UK, in September 1984 on the subject of fluid-structure interaction. The second was the International Union of Theoretical and Applied Mechanics (IUTAM) meeting on aeroacoustics and hydroacoustics held at the École Centrale de Lyon, France, in July 1985. In both of these meetings, the trend towards low Mach number problems was quite evident.

The principal European nations engaged in hydroacoustics research are France, England, and West Germany. Lyon is a major center of that activity in France with work at the Center for Acoustics and at the Laboratory for

Fluid Mechanics at the École Centrale de Lyon, the Laboratory for Vibration and Acoustics (LVA) of the National Institute of Lyon for Applied Science (INSA), and at the firm METRAVIB; see *ESN* 39-9: 427-430 (1985) for a detailed report on the latter two activities. There is also significant work being conducted in the Marseille/Toulon area, and near Paris at ONERA. In Marseille, particularly interesting work is being done at the Laboratory for Mechanics and Acoustics (LMA) of the National Center for Scientific Research (CNRS). The Centre d'Études et de Recherches pour la Discretion Acoustique des Navires (CERDAN) in Toulon and Group d'Études et de Recherches de Detection Sous-Marine (GERDSM) at Le Brusac near Toulon are two French navy laboratories engaged in ship acoustics and sonar design work. In England, the center of effort is at Cambridge: at the university and at the firm Top Express. There is also significant activity at Leeds University, at Imperial College (see *ESN* 39-5:229-230 [1985]) and at the Admiralty Research Establishment (ARE), Portland. In West Germany, the principal activities are the Max-Planck-Institut fuer Strömungsforschung in Göttingen, at the German Aerospace Research Establishment (DFVLR) in West Berlin, and at the Research Group for Hydroacoustics of the Fraunhofer-Gesellschaft in Riemeling near Munich.

Hydroacoustics research in Europe is largely theoretical. I am aware of only two active anechoic wind tunnels: one at ONERA near Chatillon, and the other at the École de Centrale de Lyon, both in France. Submerged body experiments are carried out by ARE-Portland, by CERDAN at its facility at Lake Castillon in the Maritime Alps, and also by the Research Group for Hydroacoustics at a lake in Bavaria. Such experiments, however, are few and far between. My general impression is that this field is one in which theory completely overwhelms experimental verification.

Jet and Boundary Layer Noise Theory

Several interesting developments have occurred recently in jet and

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boundary layer noise theory. Perhaps the most controversial is one related to the use of noncausal Green functions to describe both jet and boundary layer noise radiation. This development had its origins in a paper by Jones and Morgan (1972). They treated analytically a problem of deceptive simplicity--namely, the excitation of a vortex sheet separating a compressible flow of uniform velocity from a quiescent fluid by a pulsating source located in the quiescent field. The steady-state solution of this problem can be obtained. However, when this solution is Fourier-transformed in time to treat the sister problem of a transient source, the result is not causal. That is, the radiation from the vortex sheet occurs prior to turning on the line source.

The original steady-state solution constituted a bounded Green function. As pointed out by Jones and Morgan, the difficulty with this steady-state solution is that it is incomplete. It lacks the important fact that the vortex sheet itself is unstable to any disturbance and grows exponentially with distance downstream. Inclusion of this instability solution leads to an unbounded Green function, which, however, transforms to a causal solution for the transient problem.

Dowling, Ffowcs Williams, and Goldstein (1978) turned the Jones and Morgan approach around in dealing with the mean flow effect in the jet noise problem. A cylindrical vortex sheet was used to separate a turbulent jet from an exterior quiescent medium. Within the sheet, a uniform mean velocity is assumed. In this model, the serious complexities introduced by accounting for mean velocity gradients are avoided. Such a vortex sheet is likewise unstable and would tend to respond with an exponential growth downstream to any form of excitation from the turbulence inside. At this point a bold and controversial step was taken. They demanded that the Green function solution be bounded. This requires that a noncausal result be accepted--i.e., sound radiates from the

jet before the turbulence in the jet is turned on.

Dowling et al. argue persuasively that this viewpoint is a valid one. There is an inherent problem with all flow noise theories based upon the Lighthill analogy. As is well known, the Lighthill development is one in which a linear wave equation is forced by spatial derivatives of the Lighthill stress tensor. Ironically, the difficulty with the Lighthill formulation is that it is exact. Since the fluid motion equations are fundamentally homogeneous, the forcing terms so obtained mix sources with effects such as scattering and diffraction. The problem of sorting these out has been a difficulty ever since. Dowling et al. argue that since the turbulent flow is clearly bounded, the Green function upon which its description is based should likewise be bounded at the expense of a loss of causality.

A similar approach to the boundary layer noise problem was taken by Ffowcs Williams and Purshouse (1981) and by Dowling (1983). In these papers, wall flexibility is permitted. The boundary layer is modeled by a vortex sheet placed at the outer edge of the boundary layer. Möhring and Rahman (1979) take a somewhat different approach: the boundary layer is not modeled at all--a slip boundary condition at the flexible wall is assumed. Their approach appears useful in dealing with such matters as static divergence of a coating, but does not seem to be an appropriate means for studying boundary layer radiation.

It is of course possible to avoid the vortex sheet instability by using more realistic velocity profiles for both the jet flow and the boundary layer. In the case of the boundary layer, this has been done by Dowling (1984) and by Haj Hariri and Akylas (1985). Dowling concludes that the vortex sheet model is valid and determines that the proper position in the boundary layer for the vortex sheet is one displacement thickness away from the wall. Thus, in conformity with the findings of

her earlier paper (Dowling, 1983), she finds that the spectrum of downstream-traveling wavenumber components of the wall pressure spectrum for a hard wall are singular at the sonic wavenumber but that the spectrum is bounded at the sonic upstream-traveling wavenumber. Haj Hariri and Akylas used a matched asymptotic expansions approach to the same problem. They do not appear to agree entirely with Dowling except at very low wavenumbers. The complexities introduced through use of more realistic profiles make it difficult for one to compare the two analyses. They seem to afford little insight beyond that achieved with the noncausal solution using the vortex sheet model. From a purely pragmatic viewpoint, we are likely to see further use of the vortex sheet model in other analytical papers, leaving the reader to deal with uncomfortable feelings that he may develop from the lack of causality that is involved.

Unsteady Wall Shear Stress

Powell in 1960 found that for a turbulent boundary layer on an infinite rigid wall, if the unsteady shear stress at the wall is neglected, it is possible to show, by an image argument, that the entire flow field is quadrupole in nature. Therefore, it should, in an underwater application, produce insignificant radiated noise. Landahl (1975) argued that these unsteady shear stress dipoles, with axes lying in the plane of the wall, should contribute significantly both to radiation and to the low wavenumber component of the wall pressure spectrum. Howe (1979), on the other hand, using an analysis similar to Dowling's, reached the opposite conclusion. He believes that the wall shear stress fluctuation is an attenuation of an existing sound field rather than a source of sound itself. A further theoretical paper by Haj Hariri and Akylas, to be published, suggests that the wall shear stress is a weak and unimportant source of sound, a result almost in the middle between the other two.

The whole matter is of considerable practical interest because people concerned with self-noise in a sonar dome resulting from turbulent boundary layer excitation find that the low wavenumber component of the wall pressure spectrum is a potentially important source of structural excitation and consequent inward radiation of sound to the sonar transducer. This component is much weaker than the convective ridge portion of the wall pressure--that which convects at about 65 percent of the freestream velocity. However, the convective portion is, in the underwater applications, badly mismatched to typical bending wave velocities of the structure in the frequency range of interest. This leaves the low wavenumber component as a likely source of self-noise. Measurements by Martini, Leehey, and Moeller (1984) show that the low wavenumber component is some 35-dB below the convective ridge and hence is not incompatible with a shear stress source.

There is also an experimental difficulty with regard to shear stress. A comparison of measurements of unsteady wall shear by various means show a tremendous scatter. The spread in the ratio of root-mean-square shear stress to mean wall shear stress is from 5 percent to 50 percent, depending on which experimental technique was used. Thus, the whole issue of the importance of shear stress to self-noise is clouded both theoretically and experimentally.

There is another reason for being interested in fluctuating wall shear stress. When one is concerned with the excitation of a compliant surface, such as the elastic tube encasing a towed array of hydrophones, a wavenumber (or wave speed) match is possible between the fluctuating wall shear stress and shear waves in the elastomer. When this occurs, very substantial vibratory power can be transferred from the turbulent boundary layer to the elastomer via the convecting portion of the fluctuating shear stress--quite apart from its possible contribution to low wavenumber wall-pressure fluctuations. This

potentially serious self-noise problem has scarcely been touched to date.

Superdirective Noise Fields

Laufer and Yen (1983) found experimentally that a subsonic turbulent jet, excited by a pure-tone sound wave, produced a radiate sound field at the first subharmonic of the excitation frequency that was strongly directive in the downstream direction. This was related to pairing of vortices created within the jet by the excitation (see also *ESN* 39-7:331-333 [1985] for other subharmonic response experiments). Huerre and Crighton (1983) analyzed this phenomenon using the method of multiple scales. The wave packets associated with this pairing process were found to have superdirective behavior resulting from their rapid growths and decays. The calculations indicate an antenna effect resulting from delicate cancellations between growths and decays. What is very interesting is that the calculations predict the gross features of the measured directivity for a packet whose axial extent is only about one-tenth of an acoustic wavelength. Thus the term superdirectivity.

The analytical work is continuing (see Crighton and Huerre [1984]), because the theory presently also predicts nulls in the radiated field which are not found experimentally. In spite of this limitation, the concept of radiation from wave packets in turbulence has potentially important implications. Such radiation has not yet been isolated experimentally for turbulent boundary layers, although the packet behavior of wave trains has been identified at least in transitional boundary layers.

Low Wavenumber Wall-Pressure Measurements

I found no evidence that any low wavenumber wall-pressure measurements have been made in Europe to date. There is one recent theoretical paper on the subject by Ffowcs Williams (1982). He applies Corcos-like similarity to the turbulent source terms rather than to the wall pressure itself, as was done in

the original papers by Corcos. Ffowcs Williams predicts that large flush-mounted transducers discriminate against turbulent boundary layer wall pressures at a rate of 9 dB per doubling of transducer diameter instead of at the 6-dB rate previously predicted by Corcos. This is a high frequency effect which is not applicable to the entire frequency spectrum, see Schewe (1983). However, he made no comparisons of his theory with the low wavenumber wall-pressure measurements that were available at the time. I did find throughout Europe a very strong interest in conducting such measurements--particularly at ONERA in Chatillon, at the Institute for the Mechanics of Fluids in Marseille, at CERDAN in Toulon, and at ARE-Portland. Professor Comte-Bellot, director of the Centre Acoustique of the École Centrale de Lyon has purposed to conduct a joint program with my group at the Massachusetts Institute of Technology for carrying out such measurements on a glider available to their group. The use of a glider would get rid of many of the problems associated with facility noise which plague measurements in wind tunnels and would be far simpler to conduct than a rising body experiment.

Radiated Sound and Form Drag

Ffowcs Williams and Lovely (1975) published the surprising result that the average acoustic power radiated by a vibrating or compliant surface adjacent to a moving fluid is equal to the conventional average of the product of pressure times normal surface velocity integrated over the area of the surface, plus an additional term which is the product of the mean form drag times the free stream velocity. The result was derived in source fixed coordinates and is tantamount to a Blokhinzev energy calculation. For this reason, its practical applicability has been challenged--notably by Möhring in discussions at Euromech 188 in Leeds--on the basis that such calculations are difficult to interpret when one comes to the edges of the vibrating surface. I cite an example: it is possible to calculate

the form drag on an undulating airfoil in two-dimensional incompressible flow solely by determining the leading edge suction, a term which may provide thrust or drag, depending upon the nature of the undulation. The surface integral which yields the product of drag times mean flow velocity in the Ffowcs Williams and Lovely calculation plays no essential role in this case. In spite of these objections, the concept has led to a close linking of questions of drag reduction by compliant coatings with questions of acoustic radiation, which we may expect to see exploited considerably in research in the future.

Interaction of Sound With Turbulence

Let us consider the problem of sound waves traveling through a duct which is also carrying a mean flow. The mean flow creates a turbulent boundary layer on the duct walls. Ronneberger of the Third Physical Institute of the University of Göttingen has shown very recently that it is possible for the turbulent boundary layer either to absorb the sound or to generate new sound by the interaction with the sound. The question is basically one of how the Stokes wave at the surface generated by the sound wave interacts with the turbulent field. Sound waves also interact with free turbulent shear layers. Ronneberger showed as early as 1967 that sound radiated downstream through a flow-carrying duct into a turbulent jet resulted in a reflection coefficient markedly greater than that predicted by the classical Levine-Schwinger solution for radiation from an open-ended tube without internal mean flow. Here the interaction of the sound with the jet shear layer clearly resulted in more sound production. Bechert, on the other hand, has carried out other experiments where the shear layer strongly absorbed the sound. These experiments, clearly related to the Laufer and Yeh studies mentioned earlier, have not as yet been adequately explained theoretically. In some sense they relate to one of the justifications advanced for the use of noncausal Green functions. The argument is that acoustic waves can cause turbu-

lence, and therefore their appearance as a precursor of the turbulence is not unreasonable. Perhaps this is true for a jet whose shear layer grows rapidly and is inviscidly and linearly unstable. A turbulent boundary layer, on the other hand, is linearly stable and slowly growing. Only for low frequencies is the Stokes layer thick enough for the sound to interact with the turbulence. For the laminar boundary layer, which does become linearly unstable, we have almost conclusive evidence from receptivity studies--Leehey, Gedney, and Her (1984)--that high frequency sound beamed over a plane rigid wall has negligible effect upon a laminar boundary layer, except in the immediate vicinity of the leading edge. There is essentially no interaction of the Stokes wave with the Tollmien-Schlichting waves which eventually break down the turbulence. Here the sound clearly does not directly "cause turbulence." What is needed is some wavenumber conversion mechanism which is not available in the nearly parallel flow over a plane wall--for example, a bump on the surface or an adverse pressure gradient near the leading edge (see Goldstein [1985] for a theoretical treatment involving triple deck asymptotics).

Cavitation Noise

There is an upsurge of interest in the measurement of propeller cavitation noise throughout Europe. Every variable pressure water tunnel facility that I visited had in use, or was putting into use, acoustic measurement equipment. A particular interesting development is the new large cavitation tunnel being built for the Bassin d'Essais des Carenes some 95 km from Paris. One test section is really an irregularly shaped reverberation chamber which is designed to permit sound power measurements of cavitation noise on model propellers in model ship wakes. The chamber is fitted with an internal steel tube which permits the mean flow to traverse the reverberation chamber without disturbance. The model under test is located within this tube. It is expected that third-octave sound power measurements can be

made for frequencies above 600 Hz. This is quite suitable for determining most of the frequency spectrum of propeller cavitation noise, although the facility is hardly likely to be usable for determining the strength of blade-passing frequencies.

I noted two recent results in the field of cavitation noise of considerable interest. The first was obtained by Van Wijngaarden and his student Omta at Twente University, Enschede, The Netherlands. It relates to the acoustic properties of gas-filled bubbles. From research work in the past, we have come to expect that gas-filled bubbles will resonate under acoustic excitation at the resonance frequencies of the individual bubbles. Since the bubbles are usually distributed in size, this means that there is a band of resonant response in the high frequency region. Their new finding, determined both experimentally and theoretically, is that there is an additional important resonant frequency for a cloud of bubbles. This is the frequency at which the cloud oscillates and is determined as that of a single bubble with the same total gas content as the cloud. If the period of the bubble cloud is very much greater than the crossing time of an acoustic wave front, resonant amplification of the acoustic wave will occur. This result may have considerable practical importance.

The second result is one recently obtained by Lauterborne at the Third Physical Institute of the University of Göttingen, West Germany. Lauterborne has studied the near field sound radiated by cavitation created near the center of a water-filled tube. The tube wall is made of a piezoelectric material which can be driven electrically to provoke the cavitation. Lauterborne drove the piezoelectric cylinder at a discrete frequency and measured the cavitation response spectrum with a hydrophone as a function of increasing drive amplitude. A subharmonic bifurcation began at one-half the drive frequency at a low level of excitation. As the excitation level was increased, further bifurcation de-

veloped, leading rapidly to chaotic behavior. He has also carried out a theoretical study of this process using single bubble equations, neglecting surface tension and heat conduction. His theoretical results are in good qualitative agreement with his experiments.

Anti-Sound

There is a resurgence of interest throughout Europe in the subject of sound cancellation by sound for a variety of applications in aeroacoustics, in underwater acoustics, and in building and environmental noise reduction. This has been brought about in large part by the availability of inexpensive and very fast integrated circuitry for performing nearly real-time calculations to provide the necessary feedback signals for canceling transducers and also by the availability now of relatively inexpensive transducers, particularly for aeroacoustic applications. I note a tremendous change from some 20 years ago, when many professional acousticians viewed the whole subject of sound cancellation with considerable suspicion as being akin to witchcraft. We now have available a number of practical applications of cancellation techniques, and the basic theoretical principals are being investigated. Ffowcs Williams (1984) gave a review lecture on the subject of anti-sound discussing the basic principles and giving a number of applications. Roebuck gave a general survey of this topic at the IUTAM Symposium on Aero- and Hydro-acoustics in Lyon in July 1985. The gist of both theory and experiment today is that it is possible to achieve far-field sound cancellation over reasonable frequency bands. A cancellation system usually involves a number of sensors to detect the original acoustic signal. These are connected by high-gain feedback circuits to transducers which emit sound in phase cancellation.

Two principles seem to be most important. One is that the detecting sensor itself must not respond significantly to the canceling signal, for then one would have positive feedback with the

usual screech which is common in improperly adjusted audio amplification systems. The second, which is more difficult to deal with, is that one must be extremely careful of using point-source concepts in practical applications. It is important to deal always with finite-sized sources and finite-sized phase cancellation devices.

A prototype, but operational, cancellation system has been constructed by the firm Top Express for the exhaust of a gas-turbine-driven power generation system for use on land in an emergency. This consists of a series of sensors and a ring of canceling transducers around the periphery of the exhaust. It was quite successful in substantially reducing environmental noise pollution caused by the exhaust. For economic reasons the technique has not been extended to other shore-based gas-turbine-driven power plants.

A group under Dr. Paul Filippi at the Laboratoire de Mécanique et d'Acoustique of CNRS, Marseille, has an operating sound cancellation system for canceling unwanted noise in a room. It incorporates state-of-the-art microchip technology. At the Lyon symposium in July 1985, Maria Heckl made a dramatic demonstration of sound cancellation by using sound to kill the noise emitted by a Rijke tube. This is part of her doctoral work being conducted under the direction of Ffowcs Williams at Cambridge University.

Concluding Remarks

Hydroacoustics is alive and vigorous in Europe. Particularly the work in France and England overshadows that being done in the US. There are many features of the theoretical research over which vigorous controversy still rages; this simply typifies a field which is active and in the forefront of science today. My one criticism is that there should be more experimental work done to test the conclusions of literally a deluge of theoretical output.

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