THE DANIEL AND FLORENCE GUGGENHEIM MEMORIAL LECTURE

The Aerodynamic Potential of Anti-Sound

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Abstract

This lecture discusses the interface between unsteady aerodynamics, flow stability and aero-acoustics. The central theme is the possibility of carrying over from acoustics some techniques of anti-sound to improve the performance of aeronautical systems. The lecture discusses the common basis for modelling weak unsteady flow perturbations and the areas which might be suitable for the application of controlled perturbations, deliberately created to interfere destructively with some unwanted naturally occurring element. The development of aeroacoustic modelling is briefly surveyed to indicate the basis for the active control strategies, and the lecture concludes with examples of how these techniques have been applied at laboratory scale with distinctly promising results.

Introduction

Our ears sense sound by responding to unsteady aerial pressures, pressures varying on a time-scale between 1/20th and 1/20,000th part of a second being audible to the young human ear. We can sense a pressure variation as small as 10^{-10} atmospheres, the ear becoming overloaded at 10^{-4} atmospheres with pain rising to permanent damage at 10^{-3}. Those weak variations conform to small perturbation theory so the governing equations may be linearised to describe the physical acoustic process. The most useful of all properties of linear functions, that of non-interfering superposition of solutions, is the basic property that allows the simultaneous multi-channel voice communication which we know as the 'cocktail party' effect. Masking chatter does not destroy any message in an individual sound, and the brain is very adept at the kind of signal processing necessary to extract signals from background noise.

Conventional aerodynamics on the other hand involves pressures non-linearly related to the fluid motion, spreading from sources only because of vortical convection, rarely a useful information channel. Vortical flow remains weakly coupled to sound as long as flow Mach numbers are small. The pressure variations are heard only when the ear is placed close to the buffeting flow; pseudo sound has not the real sound's ability to irradiate distant regions. Neither does the maintenance of aeronautically useful local pressure fields involve the energy leakage that would be inevitable if those fields involved significant dilatation - the spring of resistance to which is the essence of a sound wave. Aerodynamically induced sound is, mercifully, weak; less than one per cent of the propulsive losses in a jet propelled aircraft appearing in its noise field. This weak coupling has made possible an understanding of flow-induced noise without having to deal at the same time with any flow-modifying influence of that noise. It has also, despite the evident non-linearity of aerodynamic devices, made reasonable the treatment of aerodynamic sound as a linear field, elements of which can be isolated and handled separately, their linear superposition being a faithful reflection of the whole.

Of course, as the subject has matured it has been recognised that the decoupling of parent flow and acoustic debris is not as complete as was once supposed. There are some instances when their interconnection is crucial in determining the character of a phenomenon - even at very low Mach number. And their intimate interconnection was always a possibility that could not be ignored at high Mach numbers. Sound could hardly escape from a body travelling at exactly its speed, so that the accumulated effect of even the smallest acoustic source is then a probable hazard. The difference between the flow speed and the speed of sound is the best measure of aero-acoustic decoupling, and the dramatic aerodynamic change, the drag build-up, that occurs at transonic speed originates in precisely this point. Waves that hang around their source, being nourished continually yet with no energetic sink, grow to grotesque forms and dominate transonic aerodynamics. The naturally placed sound wave becomes fierce when trapped. Trapping due to a pursuing body stimulates the growth of the sound wave into a shock with the necessary pace to avoid capture. Waves are always strong enough to keep ahead of the driving piston in a gun tunnel.

A more conventional acoustic effect illustrates the same tendency for energy conserving sound waves to grow to the strength necessary to resist confinement.

Resonant fields, and waves in reverberant spaces, are characterised by the fact that source excitation causes the wave strength to grow until it is big enough, despite the inefficiency of its energy dissipating elements to cope with the power output of the source[1]. To be more specific, a piston vibrating in a rigidly closed tube of length L induces at distance x from the closed end, a pressure variation that is $(\cos\omega x/c)/(\cos\omega L/c)$ times that at the piston face. The angular frequency of vibration ω is $\pi/2L$ times the speed of sound c at the first resonance frequency of the tube, at which condition the pressure in the tube (everywhere apart from the piston face) is unbounded according to the generally accurate linear inviscid theory. The mobility of the piston, the displacement associated with unit pressure at its face, is $\frac{1}{\rho c\omega}\tan\omega L/c$, which varies all the way from infinity at the resonance condition down to the value $L/\rho c^2$, (i.e. L divided by the bulk modulus) at very low frequencies. Sound waves which can be modelled effectively and their general character understood according to small perturbation theory, a theory that exploits the fact that commonplace sources are very small disturbances indeed to the natural environment, are nonetheless sometimes capable of significant amplitude. When trapped by sonically moving surfaces, or focussed into a small region or physically contained in an almost closed chamber, they can attain levels significant enough to interact with aerodynamic fields - and the possible exploitation of such interaction is the theme of this lecture.

Of course the importance to aviation of phenomena that can be understood on the basis of small perturbation theory is classically established[2,3]. The stability of an aircraft is assessed by the tendency for small deviations from the desired flight trajectory to grow or decay. That tendency established according to linear theory not only determines the boundaries of stable flight but provides a useful pointer to the characteristics of motion outside that stable range. The deviations can be small enough to comply with small perturbation theory though large enough to call for definite corrective action on the part of the pilot. And an automatic pilot correction to compensate for some otherwise natural tendencies to instability has become routine on high performance aircraft. On a faster time scale, the stability of an aircraft part, a wing or an aileron, is also characterised by linear theory. If a small deflection induces deflection-increasing loads, that will tend to aggravate the response to exterior disturbances, and at its extreme 'divergence' would result when the structural stiffness was overcome by the (negative) aerodynamic stiffness[4]. And when unsteady deflections induce an aerodynamic response which energises structural vibration, then oscillations must grow. Such flutter[5] is again well modelled by linear theory, and again small perturbation theory[6] characterises the behaviour of a control system that could be implemented automatically to suppress the flutter condition. Again this is a feature of existing aircraft technology, though probably at its leading edge.

Classically established also is the much finer scale modelling[7] of aerodynamic flows, instabilities of which lead to buffeting, unsteady stall, turbulence and noise. Linear analysis is the most adaptable tool we have for assessing stability, small flow perturbations being modelled routinely in the fundamental work that underpins the practical aerodynamic design process. The geometric complexity of instability waves here is as intricate as the Reynolds number is big, and yet distinct progress has been made in the detailed understanding of some technologically significant disturbances, the growth of large structures in shear layers[8] and the early stages of transition to turbulence[9] for example. It is even possible now to contemplate the artificial stabilization[10] and selective manipulation of distinct flow structures[11]; these studies tend to be at frequencies in the audio range and have not yet spread beyond the more academic research laboratories.

All these phenomena in which disturbances to a basic condition can be described as linear perturbations of the mean state are subject to the superposition principle that allows them to be examined bit by bit, by Fourier or modal decomposition for example. Classically the decomposition is made in order to simplify the jobs of modelling and understanding the processes at work. Now I want to change the emphasis and to exploit superposition in a different way. I want to address the issue of creating disturbances by some external control system which is tailored to produce perturbations that are the exact opposite of those occurring naturally. Once produced they can be added to those already there, the linear superposition of the two destructively interfering fields amounting to zero.

This view of actively stabilized aerodynamic systems comes from the emerging technology of active noise control[12]. There the linear acoustic field is suppressed by an artificially created field which superposes to cancel the original. The sound and anti-sound combination amount to silence. Not all silence is usefully thought of as a combination of sound and anti-sound of course, but the view is useful in ordering one's approach to the problem of artificially silencing a given noise source by a secondary acoustic system. Similarly, not all aircraft conditions will be usefully regarded as the combination of influences, each naturally unstable but compensated for precisely by a rigorously sustained generator of the opposite effect - but if the wing and tail are treated as coupled sub-systems, they do constitute precisely such a mutually compensating pair. The task of maintaining steady flight through an irregular atmosphere is on the other hand very effectively approached by seeking the control movements necessary to generate the exact opposite deviations to those that would otherwise occur.

In order to keep close to the area of my professional experience I propose now to sharpen up the *definition* and *scope* of my subject, and concentrate specifically on those aspects of aeronautical systems which lie at the *interface* of unsteady aerodynamics and sound. I will describe what I believe are the underlying physical principles important to those areas, the techniques we have for modelling them, and how close they lie to phenomena where active sound control has already been demonstrated. Firstly I will refer to studies and laboratory experiments which are providing some distinctly encouraging points that anti-sound technology is transferable in this way to useful aerodynamic devices, which can become much more useful as a result.

Sound

Weak audio-frequency disturbances to an atmosphere at rest are little influenced by viscosity; the conservative force field of unsteady pressure gradients overcome the inertia of the gas

$$\nabla p = -\rho_0 \frac{\partial \underline{u}}{\partial t} \qquad (1)$$

and the tendency towards a density build-up

$$\frac{\partial \rho}{\partial t} = -\rho_0 \nabla \cdot \underline{u} \qquad (2)$$

is resisted by the compressive resilience of the material

$$\frac{dp}{d\rho} = c^2 \ . \qquad (3)$$

These are the linear equations linking the density variation $(\rho - \rho_0)$ and the pressure p to the velocity field $\underline{u}$, c being the constant speed of sound. Cross-differentiation and a slight re-arrangement of terms show that all the flow variables then satisfy the wave equation, for example:

$$\frac{\partial^2 \rho}{\partial t^2} - c^2 \nabla^2 \rho = 0 \ . \qquad (4)$$

The small pressure variations given by

$$p = c^2(\rho - \rho_0) \qquad (5)$$

are functions of $(x \pm ct)$ in the simplest, unidirectional waves, and from these come the common understanding that sound waves involve particle velocities of $\mp p/\rho_0 c$, (depending on the wave direction) and that the vibrational Mach number $|\frac{u}{c}| = |\frac{p}{\rho_0 c^2}| = |\frac{p}{\gamma p_0}|$, rarely rises to 10^{-3}; γ is the ratio of specific heats.

Sound raises the energy level of the medium because it makes particles move and imparts to them an elastic compressional energy, both being equal in a plane sound wave at a value $\frac{1}{2}\rho_0 u^2$ per unit volume. The moving particles, with their in-phase elevated stresses, $p = \rho_0 cu$, cause energy to flow through the field, energy flowing in the direction of particle vibration (perpendicular to the wave crests) at a rate $pu = p^2/\rho_0 c = \rho_0 cu^2$ per unit area. In a steady sound field, one in which the mean (over many cycles) is not varying, the energy flux in a one-dimensional wave is uniform: what comes in on the left goes out on the right. But sound fields need not involve any energy flux; if the leftward travelling wave has the same variance (mean square) as the rightward-going wave, be they correlated or not, there can be no mean energy flux

$$p = a(t - x/c) + b(t + x/c) \qquad (6)$$

$$u = \frac{a}{\rho c}(t - x/c) - \frac{b}{\rho c}(t + x/c) \qquad (7)$$

$$\overline{pu} = \frac{\overline{a^2}}{\rho c} - \frac{\overline{b^2}}{\rho c} \ . \qquad (8)$$

Though each wave on its own would involve energy flux, the combined field is energetically neutral. It is not neutral because the rightward flux balances the leftward flux, indeed there is no such flux superposition principle. The intensity of two waves travelling in the same direction

$$p = a(t - x/c) + b(t - x/c) = \rho cu \ , \qquad (9)$$

$$\overline{pu} = \frac{\overline{p^2}}{\rho c} = \overline{a^2} + \overline{b^2} + \overline{2ab} \ , \qquad (10)$$

depends essentially on the correlation between the two waves. *Energy, and energy flux*, is quadratic in the wave amplitude, and being non-linear is not subject to the superposition properties of linear field variables.

The simplest three-dimensional waves are the centred sound waves

$$p(x,t) = \frac{f(r \mp ct)}{r} \qquad (11)$$

the $\mp$ signifying respectively outward or inward travel of the wave crests. The pressure gradient that accelerates the particles according to equation (1) now has two terms

$$\frac{\partial p}{\partial r} = \frac{f'}{r} - \frac{f}{r^2} = \mp \frac{1}{c}\frac{\partial p}{\partial t} - \frac{p}{r} \qquad (12)$$

the first being increasingly dominant as the wave-front curvature, r, becomes large; in that case the three-dimensional field evolves into a slowly varying one-dimensional field in which

$$-\rho_0 \frac{\partial u}{\partial t} \underset{r\to\infty}{\sim} \frac{f'}{r} = \mp \frac{1}{c}\frac{\partial p}{\partial t};$$

$$\text{i.e. } p = \pm \rho_0 c u \qquad (13)$$

is the familiar plane wave pressure/velocity relation.

But when the wave curvature is high it is the second term in (12) that dominates and then,

$$\frac{\partial p}{\partial r} \underset{r\to 0}{\sim} -\frac{p}{r}, \qquad (14)$$

so that the pressure is now 90° out of phase with the particle velocity.

$$\frac{\partial p}{\partial r} \sim -\rho_0 \frac{\partial u}{\partial t} \qquad (15)$$

so that

$$p = \rho_0 r \frac{\partial u}{\partial t} \qquad (16)$$

is the appropriate small r relation between pressure and velocity fields, a relation implying correctly 1) how very inefficient at generating pressure fields are highly curved sources, 2) the dynamics of highly curved fields are determined regardless of acoustic properties (the speed of sound c does not enter the result) and 3) that the dominant local motions in highly curved wave fronts involve no energy transport,

$$\overline{pu} = \rho_0 r \overline{\frac{\partial u}{\partial t} u} = \rho_0 r \frac{\partial}{\partial t} \overline{\tfrac{1}{2}u^2} = 0 \qquad (17)$$

in a steady sound field.

The cross-over between the near, curvature dominated, and the far, weakly curved, sound field proper occurs when the two terms in (12) are comparable

$$\frac{|f|}{r^2} \simeq \frac{f'(r\pm ct)}{r} = \frac{1}{c}\frac{\left|\frac{\partial f}{\partial t}\right|}{r} \qquad (18)$$

i.e.

$$r \simeq c \frac{|f|}{\left|\frac{\partial f}{\partial t}\right|} \qquad (19)$$

which is a convenient estimate of the acoustic length scale.

The mean outward energy flux $\overline{pu}$ in this centred steady wave field is, from (12),

$$\overline{pu} = \overline{\left(-r\frac{\partial p}{\partial r} \mp \frac{r}{c}\frac{\partial p}{\partial t}\right)u} \qquad (20)$$

$$= \mp \frac{r}{c}\, \overline{u\frac{\partial p}{\partial t}} = \pm \frac{r}{c}\, \overline{p\frac{\partial u}{\partial t}} \qquad (21)$$

to give

$$\overline{pu} = \mp \frac{r}{\rho_0 c}\, \overline{p\frac{\partial p}{\partial r}} \qquad (22)$$

$$= \pm \frac{1}{\rho_0 c}\, \overline{p^2} \qquad (23)$$

the sign depending on whether the wave is outward or inward propagating. Like the mean square pressure, the intensity obeys the inverse square law. The total energy crossing a spherical surface is independent of the surface size - provided that the surface includes the origin r = 0. What energy enters a volume from the vicinity of r = 0 leaves without loss through its outer boundary.

There can be no mean source of energy in any steady sound field, the mean scalar product of equation (1) with $\underline{u}$, combined with equations (2) and (3) leads directly to the continuity of energy flow condition

$$\nabla . \overline{p\underline{u}} = 0 \ . \qquad (24)$$

One last point of introduction is the central part played in acoustics, and wave fields generally, of interference effects between multiple fields. The two centred fields (centred about different points)

$$p_1 = \frac{f(r_1 - ct)}{r_1} \text{ and } p_2 = -\frac{f(r_2 - ct)}{r_2} \qquad (25)$$

are almost each other's opposites in those regions where $(\underline{r}_2 - \underline{r}_1).\nabla p_2$ is small in comparison with p_1, that being the leading difference term in a Taylor series expansion of p_2 about the source point of p_1. In the far field where ∇p has magnitude essentially equal to p divided by the wave scale, the destructive interference of the two fields evidently reduces the characteristic magnitude of the sound by the ratio of the source scale to the wavelength. The destructive interference therefore reduces the energy flow into the distant sound field (and therefore everywhere) by the square of that source/wavelength compactness ratio. The interference, and therefore the magnitude, of the residual field depends on position so the residual field now has a more intimate geometric structure. In the close vicinity of the points $r_1 = 0$ and $r_2 = 0$, the presence of the second interfering field has hardly any influence on the field's magnitude, a point that illustrates the general rule that it is the radiation away from a source region that is most critically influenced by the destructive interference of multiple fields; the source region itself, or region of highly curved wave-fronts is, as we have already seen, only weakly influenced by acoustic effects. The source region need not have many of the sound field's characteristics and in particular it need not share the acoustic field's sensitivity to interference.

Of course the interference is destructively efficient only when the waveform $f(r_1-ct)$ is almost identical to $f(r_2-ct)$. The two wave systems must be mutually coherent. Incoherent fields add in quite a different way:

$$\overline{(p_1 + p_2)^2} = \overline{p_1^2} + \overline{p_2^2} + \overline{2p_1p_2} \quad (26)$$

$\overline{p_1p_2}$ is zero when p_1 and p_2 have no coherence, in which case the variances of the sounds are additive. This is Rayleigh's[13] principle that reflects the common experience that sounds get louder when sources participate.

The destructive interferences between opposing coherent fields[14] is formalised in the 'multipole' representation of fields. For the purposes of this lecture three properties of multipole structures have a bearing on my general theme 1) source interference effects are guaranteed only when the complete source system is acoustically compact; 2) when that is so, it is probable that the simplest isolated source is dominant and 3) delicate and precise destructive interference is easily distorted by extraneous effects; the acoustic output of a complex compact multipole is very easily increased - by the simple device of suppressing any one part of the destructive field.

Aerodynamic Sound

The aeronautical concentration of high power in compact machines made aviation's high acoustic profile inevitable. Today, with the jet noise problem largely checked by new technology, a large aircraft taking off from Heathrow still makes more noise than could London's entire population shouting in unison. The prospect that high-speed propellers will soon power large aircraft is bound to keep the noise issue alive. There are those whose memories of past aircraft are especially vivid on account of their strident propellers, and there is no lack of expert knowledge that the propeller is a fundamentally more efficient noise maker than is the jet. **And** the propeller's noise annoys the paying passenger.

There is another reason why aerodynamic noise is technologically important today. As the subject has been better understood[15] the distinction between aero-acoustics and unsteady aerodynamics has become blurred. And the demonstration that active noise control is feasible[16] implies also that performance benefits might follow the introduction of those techniques into main-stream aerodynamics. So I return to my main theme that advanced acoustic technology can transform our perception of the subject. An extension of the operational envelope of some aeronautical systems is a prospect currently emerging from the aero-acoustic community. Before I explain the details of that issue let me first give you a lightning tour of what I regard as the technological highlights of aerodynamic noise, a tour from which I hope to demonstrate the maturity of the subject.

It was the aeronautical noise issue that prompted the expansion of acoustics to embrace the question of 'what <u>creates</u> sound'. It was remarkable that such a fundamental question should not have been asked (and answered) before, because the understanding of sound, once created, was highly developed before aviation began. **But** it was not until Lighthill's[17,18] remarkable theory that source mechanisms began to be properly understood. Lighthill proved an exact analogy between the real sound field, generated by and emerging relatively well ordered from a chaotic turbulent flow, and an easily calculated equivalent field. That field is what would be generated in a perfect linear medium at rest by certain quadrupole sources. He gave an expression for the strength of those sources in a tensor that now bears his name. Lighthill pointed out that the source and sound fields, though sharing a common time scale, could have different length scales. Low Mach number flow would generate a large-scale sound because the ratio between the distances covered by sound and flow in the same time is the Mach number which is therefore also the compactness measure of the quadrupole source. Due to destructive interference quadrupole fields suffer two powers of the compactness ratio attenuation from an aerodynamic field in which the pressure otherwise scales as ρu^2. Sound pressure proportional to the fourth power of velocity then leads directly to the subject's most famous law - Lighthill's eighth power law for the acoustic power output of a jet. The theory became at once a foundation stone and a straightjacket. The concept was not easy to grasp, as is clear from alternative theories that followed[19,20,21], yet its power and elegance were evident to a degree that it took an awesome hold on the subject. The quality of experiments seemed then to be measured against the U^8 law more than was the relevance of that law tested by experiment. It took time[22] for the theory to be seen as describing precisely the properties of definite source models and for observed differences to be interpreted[23] as clear indications of different source processes.

The inefficiency of the compact quadrupole radiator, was consistent with measurements that showed jets to radiate only a small fraction, $10^{-4}M^5$, of their mechanical power as sound[24]. Attempts to manipulate jet turbulence into a quieter form by inserting 'fingers' or obstacles into mixing flow tended to increase the jet's acoustic output[25], the devices disrupting the natural destructive interference between elements of the quadrupole array. Source convection with its attendant Doppler contraction of acoustic wavelength reduces the degree of destructive interference, an effect which takes on an extreme form when the sources move supersonically[26]. The consequences of that change, the tendency for very high speed jets to generate what are essentially ballistic shock waves of supersonically moving eddies, were also readily anticipated through Lighthill's theory[27]. So eventually was the fact that many elements of jet noise were observed to be inconsistent with the simple interpretation of the theory taken as the clear signals they were that yet unmodelled aspects of the flow harboured important source effects[28]. The degree by which the noise of the lower speed jets exceeded the U^8 extrapolation of what was considered as pure jet noise led to the search for sources of the 'excess' noise[29] and that step probably marked the beginning of a more systematic stage in the subject, where deterministic effects were carefully modelled[30] and measurements were made and interpreted in much greater detail than had been past practice. And with that phase emerged a different perspective on the subject. The sound field was not now so much regarded as a 'limp' by-product of the main flow, a flow that evolves essentially independently of the sound, but rather it began to be appreciated that small disturbances can have unexpectedly large effects[31]. It was also realised that inhomogeneous flow can have a considerable modifying influence on sound propagating through it[32,33]. That is a different view of what is possibly the same phenomenon, the modifications to a propagating sound wave, if regarded as the interference effects of secondary waves simply emphasises the point that the flow can be provoked by sound to generate an acoustically significant response.

There is a wide variety of familiar examples in which vibration and acoustical effects induce order into an otherwise chaotic flow. The screech cycle[34] of a supersonic jet is sustained by the response of the jet to the sound field that response creates[35,36,37]. The motion of a long cylinder in cross-flow due to unsteady loads created on it by vortex shedding[38] is known to serve as a stimulus to the coherent vortex motions in the phenomenon of 'galloping' cables. The collapse of the Tacoma Narrows bridge resulted from such an effect. Acoustical/vortex shedding blade load oscillations are inextricably linked in the turbomachinery response phenomena bearing Parker's name[39]. The edge-tone[40] derives its order from a sensitivity in a vortex layer to sound generated by eddy/edge interactions, and most woodwind musical instruments make sound only because the acoustical response of the system has a phase-locking back-reaction on the vortex shedding mechanism that drives a cavity into resonance[41]. The acoustical response of a resonant cavity need not be at all small; it is inversely proportional to the damping of the system which is essentially small if oscillations are to be maintained over a musically significant number of cycles. The jet's response to noise is not yet so well understood, but the fact that it does respond is one of the most hopeful indications that jet mixing properties, and all that entails, will one day be subject to control.

I refer to the aspect of the subject originating from the concurrent but independent observations made by Bechert[42] in Berlin and Moore[43] in Derby that the broad-band noise of a round jet could be changed by as much as ten decibels by seeding the jet with upstream sound, the sound itself representing only a minute change to either the nozzle exit velocity or jet pressure. The jet flow, when visualised by a multi-exposure system coherently locked to the acoustic 'seed' displayed an order that was startling and exciting. Furthermore, by a multi-exposure visualization technique triggered by significant events in the naturally mixing jet, it became evident that the especially noisy parts of the mixing flow had a consistent structure, a structure that bore distinct similarities to that ordered structure that is artificially provoked by acoustic seeding. Much of this structure is now known to be consistent with deterministically computed instability waves[44] on the jet's mean vortex structure. The distinctly visible triggered eddying flows have fascinating evolutionary properties[45], where eddies are observed to 'pair' and amalgamate[46] quite suddenly. There seem to be many instances now where the cascading development of turbulence into smaller and smaller scale takes place in abrupt transitions, and that is a sufficiently different view from the past that few observers can deny seeing in it some feeling of excitement and anticipation[47]. The jet which in the past had been viewed as flow noisily careering out of control into turbulent debris might after all be subject to external control - and control at low energy levels. The subject is still probably at the stage where jets are being 'poked' here and there with various types of stimulus just to see what happens, developing slowly to use more sophisticated stimuli as understanding grows. Multiple frequency phase-locked excitation results in Reynold's[48] 'ballooning' jet, an effect akin to the splitting of a flame by sound, a classic example of Tyndall's[49] experimental skill. Multiple stimuli can also be tailored[50] to induce a single frequency response in a jet that non-linearly distorts its input very quickly. Who is to know what this will lead to when enough is known about jet response to monitor the flow and feed-back stimuli controlled to provoke a desirable response?

All that is perhaps an unreasonably fanciful view of the jet mixing/jet noise problem. The cynic could remark that these effects are still confined to the laboratory jet of small scale, with uncharacteristically tailored flows from nozzles of technologically insignificant shape. The high speed round jet is not interesting because it is too noisy, and very rapidly mixing quieter jets seem to be insensitive to seeding. Certainly there are other more obviously viable aeronautical candidates for anti-sound technology. Though the jet is still the big prize, the propeller is a much easier case to handle. Indeed the long-term prospects of large propeller-powered commercial aircraft might rest on the ability of active cancellation technology to render them acceptable from the passenger point of view. I do not anticipate any more than I do for the jet case that anti-sound will be used to 'broadcast' silence from large aircraft. The unsteady pressure levels on a propeller and therefore also near it, are simply too big to be cancelled by anything other than another appropriately engineered propeller! And that is effectively what is done when blade numbers, geometry and sizes are chosen to constitute an acoustic array of minimum radiation efficiency. In detail, the patterns are analysed into a superposition of disc modes, the coupling of each mode being known provided acoustic/flow interaction effects are negligible. The contribution of each part of the propeller blade to each mode is usually assessed on the basis of linear acoustic theory that allows surface fields to be analytically continued to the far acoustic field[51,52]. Whether that is best done in modal terms, and precisely when the frequency decomposition is best made is a detail. What is certain is that any technique is wrong that fails to emphasise the acoustic danger of highly loaded surfaces travelling uncontained at the speed of sound. It does seem possible that fear of an inexorable increase of noise with speed could mislead the designer into keeping tip speeds in the low supersonic range whereas a wiser design axiom might be 'avoid the neighbourhood of Mach one'. Some forms of supersonic blade noise for a given aerodynamic duty will be a decreasing function of speed[53]. That is the prediction of linear theory for reasons not disassociated with those accounting for the transonic drag rise.

The reason for looking for active noise control solutions for the advance propeller aircraft does not yet concern the control of noise at source, nor the community noise aspect. It is seen more as a way of containing the cabin noise and vibration problem, a low frequency problem that is likely to be more elegantly and efficiently treated by active than by passive means. And that brings me finally to the point of summarising what the current prospects are for the aeronautical application of this kind of technology.

Anti-Noise

'Multipole fields' is the name we give the naturally occurring destructive interference systems which are highly inefficient wave radiators when acoustically compact. One of the most potent noise suppressing effects in the ocean exists because sound is reflected at the air/sea surface with opposite phase, the reflected field cancelling that of a nearby underwater source. Passive noise control strategies should always reflect the potential gain of destructive interference just as much as they are sensitive to the pressure doubling effect of nearby solid boundaries. A low frequency vibrating panel with an odd number of half-waves is quiet relative to its even-numbered counterpart because of destructive interference. Anti-sound on the other hand is the name given to electronically controlled secondary sources which are driven deliberately to supplement a pre-existing field and to interfere destructively with it[12]. The versatility of electronic control allows 'on-site' adaptation for fine-tuning of the system and also admits the possibility that systems with slowly varying characteristics can be 'tracked' and silenced by an adaptive controller. Once an active solution has been found, and defined completely, the chances are that it might be engineered also by more conventional passive means. It is self-evident that in the 'active control age', where matching of sound and anti-sound must be maintained to high levels of precision, the general understanding of the system is likely to be of a different order from the good old days where errors could be scaled down logarithmically and quoted in decibels.

It is important to be convinced that there exists a noise-control strategy that leaves the noisy device otherwise unharmed. Destroying the engine is not a satisfactory way of silencing it. For that conviction one needs only appreciate the total equivalence of a light field re-created by a hologram with that of the real thing, to know that wave fields can be identical over large regions of space yet have quite different sources[54]. A phase change then allows sounds to be *silenced* by sources which are not the opposite of the primary sources; but their sound fields must be opposite. There will be activity in the immediate neighbourhood of the source, of course, but what we are addressing now is the idea that there can be sound fields that remain confined to their source area, confined there because the complete source system, source and anti-source, constitutes in the external field a destructively interfering and therefore silent wave system.

The Busemann biplane[55] is precisely such a system, where the wave field of the upper wing is the exact opposite of that of the lower wing in the external field. The two together constitute a source and anti-source system in which the waves are contained internally - despite the unobstructed connection of the internal space to the outside world. Precisely the same phenomenon can be identified for unsteady wave fields originating in a channel from sources asymmetrically arranged about the axis of symmetry. At low frequencies only even order wave modes can propagate in the channel so that the odd wave activity is there exponentially confined to the vicinity of the sources, and negligible wave coupling results from the open channel ends. The energetics of these anti-sound systems run contrary to one's intuitive feeling that noise sources are inevitable suppliers of acoustic power. There is no power flow at all in the above examples, and it is easy to construct devices which are 'activated' to absorb and not to produce energy. The point acoustic source can be driven so as to absorb from a plane sound wave the energy flux that would normally flow in an area $\lambda^2/4\pi$, λ being the acoustic wavelength. This is no more unnatural than the known ability of absorbers to extract useful energy from waves on the ocean surface. This part of the subject has been demonstrated many times now in various laboratories around the world and I will refer to some specific examples to indicate the level of technology in the subject.

First there is the device invented by Olsen and May[56] where noise is reduced in the vicinity of a single microphone by playing into the microphone with a nearby loudspeaker, a (negatively) amplified version of the microphone signal. The microphone hears then the noise $p_iA(p_i - A(p_i - A(p_i - A(\ldots etc!!$, A being the amplification ratio and p_i the incident sound. The series is simply $p_i/(1 + A)$ showing how the environment of the microphone is silenced by the factor $(1 + A)$, which can easily be made very large. Stability difficulties soon arise when this technique is attempted in large open spaces where people move in to listen to the silence, but in small confined regions of constant geometry, the ear-cavity in a pilot's head-set for example[57], this technique is straightforward to apply and can be very useful. I understand that it is on the verge of practical application in several military configurations at the moment.

The second well-studied category of anti-sound demonstrations concerns sound in a wave-guide[58], trapped to a degree and tending to a modal structure that reflects the confining geometry of the guide. Modes can be excited by sources with widely differing characteristics, so that anti-sound control of modal fields is generally a simpler matter. It is simpler because there is inevitably a well-ordered spatial structure to the modal elements whose amplitudes are limited by damping that must be small if the mode is to protrude above the background. The small damping that limits the amplitude of the 'organ-pipe' resonance is easily augmented by active means[59]. And the one-dimensional waves, whose *reflection* at the open ends brings about the coherent interference that constitutes the 'organ-pipe' mode, are easily monitored and created in anti-phase by a loudspeaker further down the pipe[60]. This class of duct noise absorber is perhaps the most popular of all laboratory demonstrations at this time[61], its popularity reflecting the fact that the enabling technology is widely available. Forty decibels of control is not uncommon for single harmonic tones and repetitive periodic sounds, while 20 decibels seems to be a reasonable attenuation level for wide band-width random noise, two octaves or more being within today's laboratory technology[62].

A combination of both the Olsen and duct mode schemes leads on directly to silencers that prevent the escape of sounds from open pipe ends. Small engine exhaust pipes emit period sounds which are easily mimicked in anti-phase by a loudspeaker driven with a repetitive signal synchro-phased to the engine and adapted continuously to best cancel the exhaust noise[63]. This is the area in which has been developed what is probably the biggest anti-noise suppressor made so far[64]. The forty megawatt Rolls-Royce Avon gas turbine that drives the British Gas compressor at Duxford normally exhausts through a ten foot diameter pipe with passive silencers attenuating high frequency noise. But the residual low frequency rumblings that are difficult to control by conventional means are suppressed there by anti-sound. Seventy-two large loudspeakers supplied with one kilowatt of controlled electrical power annihilate the rumble, 15 decibels of attenuation being reported.

In my own laboratory at Cambridge[59],[65],[66] students have researched the use of anti-sound techniques for a range of phenomena, with success coming from a varied application of skill, endurance and ingenuity. Their experience in controlling and attenuating the noise of wind tunnels, turbulent flames, printing presses, electrical transformers, anechoic chambers and Rijke tubes reinforces similar experience at the Universities of Essex[63], Lyon[67], Southampton[68] and Marseilles[69] and reinforces the view that anti-noise technology is ready for serious applications. The world-wide interest in the subject is immense and its literature is already substantial, Guicking's[70] splendid annotated bibliography lists over 800 references and the first text book is expected shortly[71].

Nowhere is the drive to new technology as intense as in aeronautics when a new need is realised, and it is in aeronautics that I expect to see the early application of large-scale anti-sound, the control of cabin noise levels in advanced propeller-driven aircraft being something within reach of techniques familiar to University researchers. Vibration issues are also likely to be substantial with those advanced propeller systems, and their low characteristic frequency makes them good candidates for active vibration control, a technology developing hand-in-hand with anti-sound. But perhaps the most challenging of all the ideas in this area comes from the merging of unsteady aerodynamics with anti-sound. There are early indications that real performance improvements are feasible with these techniques. That is the central message of this lecture.

Smart aerodynamics

I take the heading from Epstein's[72] stimulating paper in which he foresees miniaturisation of reliable and cheap computing power leading to extensive and continuous matching of adaptive engine components. Future systems will maintain an optimal matching over the entire operational envelope, variable geometry elements being controlled by signals processed from data monitored to give minute details of the engine's condition. This adjustment to adapt quickly to changes in the 'steady' state has its natural extension to really unsteady phenomena, some of them so naturally uncontrolled and vigorous as to make unattainable what are otherwise desirable operational regimes. The phenomena of surge and rotating stall are two such examples.

Surge results from the variability of a compressor's pumping performance with changes in its throughput. Surge oscillations grow when periodic fluctuations involve more work input from the compressor than can be dissipated in the throttle, a larger plenum volume making for a more 'springy' flow system. Such natural oscillations grow exponentially, the small background disturbances randomly triggering the unstable modes that can build up into a major stall with a high damage potential. The mechanism of this build-up has been thoroughly studied and knowledge has advanced to the point where the condition is now thoroughly understood[73]; the operational regimes prone to surge are strenuously avoided. But if there is mounted within the system a (weak) generator of surge-like disturbances driven, not by the random background disturbances but by a signal derived from the monitored state of the surge in the compressor, then the secondary surge waves can be arranged in anti-phase to those occurring naturally to interfere with them destructively. Early theoretical studies[74] of this idea have been extremely encouraging and the first experimental demonstration of this kind of 'anti-surge' has just been achieved[75]. A loudspeaker in the plenum chamber downstream of a compressor has been activated to bring the system out of a surge-induced stall and to maintain stable (controlled) operation in an otherwise inaccessible region of the compressor map. It is only a small turbo-charger - but the conclusive demonstration that the theory is right is a marvellous pointer to a potentially useful new technology.

Rotating stall[76] in a compressor is another hazardous flow condition which is frequently the precursor of surge and stall. Recent years have seen theory and laboratory experiments developing together to the point now where the dynamics of the process are thoroughly understood. Rotating stall is initiated when the mean operational conditions are such that small amplitude disturbances, local to the compressor apart from a vortical wake, grow exponentially according to linear theory. If this is <u>really</u> the way it happens, then while the stall wave is still young and weak it can be monitored (the theory[74] identifies its distinguishing characteristics very clearly) and a 'stall wave inducer' activated intelligently to induce the exact opposite of what is there already. The linear superposition of the natural and artificially generated waves amounting to zero; the combination of basic system plus the controller is stable. Theory[77] indicates that the most unstable modes have a very simple structure which is easily duplicated artificially. The secondary generators need not be scaled to cope with oscillations of the fully-developed stall cell's magnitude, and the huge unsteady energies encountered in the rotating stall cell of an aeronautically significant machine are no guide at all to the power requirements of the controller. They do not even indicate the sign of the power flow. The idea is to catch the wave in its infancy and to destroy it before it has any significant energy - the superposition may involve extracting the energy from the naturally growing disturbance. But this should not be thought of as a possible new source of electrical power - the whole point is that the power must be small if linear superposition and the desirable wave interference is to be guaranteed.

It is too early to know whether this scheme will be successful in laboratory experiments, but the best theoretical understanding of the phenomenon provides a model with a high degree of controllability. Stable compressor operation in extensive regions where the positive slope to the 'characteristic' guarantees that the 'uncontrolled' compressor will stall are now predicted, and if this is true aircraft propulsion engines will be much more versatile than in the past. If it is not true then there will be evidence that a great deal more is to be learnt about this aspect of unsteady compressor aerodynamics, and the learning process is helped by these active interaction schemes. When a flow is maintained in a stable and therefore quiescent state by active control, there follows the switching off of that control the most perfect experimental realisation of conditions previously found only in the theoretical model. The linearly unstable wave growing exponentially on a uniform background is no longer simply the theoretical construct of the part. The wave's naturally virulent character usually guarantees that it destroys its host flow which in consequence cannot be established.

This kind of testing of linear theory by switching off the control that kept conditions stable has been very effectively used in another acoustic experiment[59] with possible aeronautical implications. As a result the Rijke tube phenomenon is now much more confidently modelled than in the past. That is a phenomenon in which a combustion system releases heat to excite confined waves, modes, which grow on the energy they provoke from the combustion process. The waves are easily modified with a microphone/loudspeaker system and the control of Rijke tube oscillations has become one of anti-sound's most interesting portable demonstrations. There are of course many aeronautical combustion systems[78] with malfunctions known to originate in thermally excited waves, and all these are in principle subject to this kind of active control, a control which offers the prospect of extending the operational range into regions otherwise prohibited on account of damaging oscillation.

The re-heat system of high performance aircraft is a rich source of discrete noises, more or less damaging depending on their precise type. The principal performance-limiting oscillations of 'buzz' and 'screech' are distinct wave phenomena which offer enormous scope for the applications of intelligent wave superposition. Developments now being reported[79] leave little doubt that we are currently witnessing in the research laboratories the birth of a new technology, a technology that not only suppresses noise, but renders stable some previously unusable flow conditions. The 'smart' cure goes beyond the symptom to control the disease.

One of the most fascinating experiments in the acoustic control of flow provides my last illustrative example. Loudspeakers are usually used for making sound, an essentially weak phenomenon involving small pressures, forces and power. But the forces are not necessarily small; the weak pressure disturbance applied in phase over a large area can induce on that area a force considerably bigger than that on the loudspeaker - by the same principle as the hydraulic force amplifier. And it can happen that loudspeakers in a flow can provoke the flow into an interesting response without inducing very much sound pressure; the response of a vortex layer is more to do with kinematic conditions than it is with pressure fluctuations. Loudspeakers have the property of being well developed for making easily controlled movements of nearby air. Wing flutter is a classic example of small deflections that induce 'deflection-encouraging' changes in aerodynamic load. And an appropriately positioned loudspeaker can disturb the flow incident on a wing, the disturbed flow in turn deflecting the wing. Now if the loudspeaker, weak though it is, is driven from a signal controlled to reflect the vibrational state of the wing (when the wing is vibrating with infinitesimal amplitude) then the loudspeaker-induced wing vibration can be conditioned to be the opposite of that already there. In this way wing flutter is suppressed by the acoustic field. The experimental demonstration that this is so reveals also that it is not so dependent on very small wing motions. A fluttering wing has been stabilised[80] by switching controlled power to a loudspeaker mounted on the wall of a wind tunnel, the energy of wing oscillation being extracted by the flow over many cycles on account of the change made by the loudspeaker to the aerodynamic damping of the wing.

That definite experiment in which the apparatus of acoustics is shown to control a flow condition harbouring traditional aeronautics hazards, is a physical embodiment of a general principle. The theoretical foundation of acoustics is available and potentially capable of extending our knowledge of unsteady aerodynamics. And the principle of anti-sound comes with the package. When this is incorporated into schemes for going beyond the state where flow oscillations are understood, designed out or avoided by bounding the operational envelope, then 'friendly' disturbances can be tailored to superpose and cancel the damaging ones. Performance advantages must accrue from the opening up of previously forbidden areas. Of course I am describing now a field becoming accessible for other reasons. Active control systems are known to stabilize otherwise uncontrollable flight systems and active flutter control has developed independently(6). But the acoustical connection will help broaden the horizons of the subject, and that will be good. Furthermore the aeronautical acoustician will be eager to help apply his technology for performance improvement; for too long have noise controlling devices been regarded as a performance penalty to be tolerated only if the public insist. It should do much to raise the level of the subject when the benefits of skills acquired in harnessing the noise of aviation are appreciated also to be useful skills concerning aerodynamics generally. If I have brought closer the day when acoustics and unsteady aerodynamics are recognised for what they really are - two parts of essentially the same subject, then I will have achieved my objective in this lecture. I will feel also that Daniel Guggenheim, who was always at the forefront of new technology, ruthlessly replacing old methods with new, would not be displeased with that result. I see my aim of changing the role of aeroacoustics and bringing it to the mainstream of aerodynamics as not dissimilar to his shifting of the emphasis from stunt flights to the safe unsensational flying of passenger traffic. And just as safe flying retains much of its pleasurable aspects, so too I hope will acoustics retain its clear discipline when properly integrated into mainstream aerodynamics.

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