Noise and Acoustic Fatigue in Aeronautics

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Introduction

The subject of noise in aeronautics needs little introduction; it has introduced itself to the world at large over the past two decades. The enormous increase in power of aeroplane engines over that period has led to aeronautical noise being a major social and scientific problem. Acoustic fatigue has followed in its wake, being the fatigue of the aeroplane structure due to the merciless hammering of the fluctuating sound pressures. Fortunately, the fatigue failures have not been catastrophic, but rather have constituted an intense nuisance. Nevertheless, acoustic fatigue is a serious enough problem, as well as noise itself, to warrant careful attention in the early design stages of aeroplanes or engines.

Although the science of noise and acoustic fatigue is a very small part of the whole science of aeroplane design, it draws upon several widely-different scientific disciplines. At the source of the problem is aerodynamic turbulence, which is a stochastic process in a viscous flow. The generation of noise at this source and its subsequent propagation involves fundamental acoustic theory. The vibration response of a structure to the noise pressure is a problem in applied mechanics and dynamics, while the subsequent fatigue failures in the structure involve metal physics and metallurgy. Experimental studies of acoustic fatigue and noise bring in the disciplines of instrument technology, while the testing techniques require a sound understanding of the principles of engineering design.

Since specialists in the problem of noise and acoustic fatigue must be acquainted with such a wide field, several short courses on the subject have been given at the University of Southampton over the past twelve years. The success of these courses (and also of an identical course given in Dayton, Ohio, U.S.A.) prompted us to present our lecture notes in the more permanent form of this book. In this, an attempt has been made to introduce the reader to the fundamentals of the various disciplines involved, and within a relatively short space to show how these disciplines have been developed and linked to study the whole problem. Much that is contained is necessarily but an outline of developments along these lines, but with several lists of references provided, the full details may be acquired by further reading.

The first three chapters of this book deal respectively with the elements of the theory of sound generation, propagation and transmission. The fourth chapter introduces the statistical theory required to handle random processes, after which the theory of aerodynamic noise is presented in Chapter 5. This outlines Lighthill's theory of sound due to turbulence, and subsequent developments.

Before specific noise sources are considered, the subjective assessment of noise is dealt with in Chapter 6. The different units of noise measurement are introduced and the annoyance and interference levels are discussed. Chapter 7 then reviews the practical results of noise measurements from jets and rockets.

The noise inside a high-subsonic or supersonic aeroplane derives primarily from the turbulent flow of air over the outer surface of the aeroplane. The associated pressure fluctuations on the surface can have magnitudes of the same order as those produced by the jet engine. The magnitudes and statistical properties of these boundary layer pressure fluctuations are discussed in Chapter 8.

Propellers of turbo-prop engines and helicopter rotors are prolific sources of noise. Accordingly, these sources are dealt with in Chapter 9.

From the newer generation of jet engines with high by-pass ratios the noise generated by the larger diameter compressor under landing conditions has become very important. Chapter 10 deals with the mechanisms of compressor and fan noise, the propagation of noise along the duct and radiation from the intake.

Chapter 11 deals in two main sections with the reduction of jet noise, firstly in relation to aeroplanes in flight (including jet-helicopters, V/STOL aircraft, etc.) and then in relation to aircraft on the ground. The use and limitations of ground mufflers, screens, test-pens, etc., are considered.

The final chapter on noise sources deals with the problem of sonic booms. The propagation and intensity of the boom are discussed, together with the effects of focussing, aircraft speed and weight.

The next eleven chapters deal with the two-fold effect of the incident noise on the aeroplane structure, viz. the vibration response and fatigue of the structure, and the noise transmitted by the vibration into the enclosed cabin. A theoretical approach to the prediction of stress levels is presented, utilizing the 'normal mode' method of vibration theory. From the theory, the principal structural and excitation parameters are identified, which govern the vibration stress levels. Thus it has been possible to outline some of the measures which can be taken to extend the fatigue life of the structure and to attenuate the transmitted sound pressure level. Aspects of the practical testing of structures for acoustic fatigue are also discussed.

Chapter 13 is in the first place, a 'revision chapter' of harmonic vibration theory, but then proceeds to introduce the subject of structural response to harmonic sound fields. Chapter 14 extends the theory to include random excitation and response. In both chapters, it is assumed that the normal modes of the structure are known, and are well-defined. Chapter 15 discusses the types of vibration mode that may be excited in an aeroplane structure consisting of thin stiffened plates.

There are very many modes which can participate in the structural motion to some degree or other. It is often found, however, that one or two modes dominate the response spectrum, and that a simple calculation based on just one appropriate mode of vibration can predict a stress level to an acceptable degree of accuracy. This simple approach is discussed in the first part of Chapter 16. On the other hand, some acoustically excited structures respond more-or-less equally in very many modes of vibration. This feature has led to the development of the so-called 'Statistical Energy Method' of analysing structural response which is becoming increasingly well-known. The second part of Chapter 16 introduces the underlying ideas of this method.

Chapter 17 considers the design of stiffened plate structures for maximum acoustic fatigue resistance. One method of achieving this resistance is to increase the structural damping, a subject to which the whole of Chapter 18 is given. In Chapter 19, the design and operation of acoustic test facilities are discussed.

The fundamental mechanisms of fatigue damage in structural materials are described briefly in Chapter 20. The cumulative damaging effect of random loading is dealt with in Chapter 21.

The concluding Chapters (22 and 23) deal respectively with the problems of calculating and reducing the noise transmitted into an aeroplane cabin. A simple, approximate theory is first presented and its limitations are emphasized. A review is then given of the more sophisticated methods of calculating the internal sound levels arising from the boundary layer pressure fluctuations on the cabin exterior, particular emphasis being laid upon their limitations. The final chapter then treats of the theoretical and practical aspects of sound-proofing aeroplane cabins.

Although the main thrust of this book is towards aeronautics the principles may be applied to many other technologies. For instance, they may be applied directly to the problem of acoustic fatigue in nuclear power plants, where fan noise can excite intense random vibration of the walls of heat-exchanger ducts. The chapters on the generation of aerodynamic noise, sound propagation and compressor noise are applicable to ventilation noise problems. The chapters on random processes and random vibration can be applied to the study of the vibration of tall chimneys excited by atmospheric gusts, or of dams shaken by earthquakes.

The chapters on sound transmission and sound-proofing are applicable to noise problems in passenger vehicles of all types; road, rail, sea and air. To this list other problems can be added, and the list is continually growing as new problems of noise and random vibration emerge.

This book has come into existence by a process of evolution extending over several years. New chapters were written and old ones were modified as each of the short courses were given. In more recent years, one half of the contributors left Southampton for the four corners of the earth, and some of the research studies they led and wrote about are no longer actively pursued at Southampton. However, their interest in the subject has continued, and by maintaining contact with us they have added to the strong international flavour of our work on noise and acoustic fatigue. This began with collaborative programmes of research work with overseas groups such as University of Minnesota, Sud-Aviation at Toulouse, and the U.S.A.F. Materials Laboratory at Wright Field, Ohio, and continues to this day.

The authors are indebted to many who have assisted or encouraged them in the preparation of this book. The work of many other investigators has provided much information and data which is included. The scale of the research work and its wide coverage at Southampton, out of which grew the courses in noise and acoustic fatigue, was only possible through the generous sponsorship of the Ministry of Aviation (now Technology) and of the European Office of the United States Air Force. Special thanks are due to Mr. Walter J. Trapp (of Wright Patterson Air Force Base, Dayton, Ohio) for his interest in the acoustic fatigue programme and for sponsoring the short course we gave in Dayton in 1961. Out of this course came the first requests for this book. Mr. Trapp has waited long and patiently for it!

We are indebted also to our long-suffering publisher, Messrs. John Wiley & Sons, and their printer, who have made such a fine production despite the insufferable delays and procrastinations we have caused.

Finally, those of us still at Southampton must record our indebtedness to our co-editor, Dr. E. J. Richards, who built up and led the noise and vibration team with inspiring zeal over seventeen years. His elevation to the Vice-Chancellorship at Loughborough University was more than well-deserved and we feel privileged to have worked under his direction. Sixteen of the contributors to this book would wish, if it were possible, to dedicate this book to him!

Contents

CHAPTER 1

An Introduction to Sound Radiation and its Sources

1.1 The nature of sound

If a taut string be disturbed laterally, a transverse wave will run along the string at a definite speed. Longitudinal pressure waves travel similarly down a rod, or through the air in a pipe. Such air-borne longitudinal pressure waves arriving at the ear cause vibrations of the eardrum, which are in turn interpreted as sound by the auditory nerves and brain.

The speed of these small pressure waves in a particular solid or fluid is called the 'speed of sound' in that material. To establish what properties of the material determine the speed of sound and the nature of sound fields associated with various types of sound sources, it is necessary to investigate the dynamics of sound waves in some detail.

1.1.1 *Dynamics of plane sound waves and the speed of sound*

Suppose that the material disturbed by the wave moves only in the direction of propagation, x. Consider a mass of material occupying a cylindrical volume of unit cross-sectional area, the ends of the cylinder being initially the planes x and $x + \delta x$. Let ξ be the displacement, measured from x, of the layer of material initially at x. Then at time t, when the displacement of this layer is ξ, the displacement of the material initially at $x + \delta x$ will be $\xi + (\partial\xi/\partial x)\partial x$. The increase in the volume occupied by the mass of material is $(\partial\xi/\partial x)\delta x$.

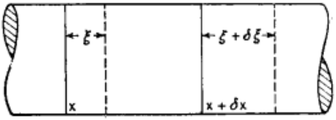

Fig. 1.1 Deformation of a material element by a plane acoustic disturbance.

The mass of the cylinder of material under consideration is constant so that there must be a density change, the density ρ being related to the initial density ρ_0 by

$$\rho_0 \delta x = \rho\left(1 + \frac{\partial \xi}{\partial x}\right)\delta x.$$

It is convenient to express the density in terms of the initial density ρ_0 and the 'condensation', or fractional change in density, $s = (\rho - \rho_0)/\rho_0$. Then

$$\rho_0 \delta x = \rho_0(1 + s)\left(1 + \frac{\partial \xi}{\partial x}\right)\delta x,$$

or, to first order for small values of the condensation,

$$s = -\frac{\partial \xi}{\partial x}. \qquad (1.1.1)$$

For a wide range of conditions met in practice, it may be assumed that the expansions and compressions of the layer, caused by the wave passing through it, are so rapid that a negligible amount of heat is lost from the material element through thermal conduction (which is a slow process) and also that there are no other appreciable heat losses. In this case the pressure p and the density ρ are related by the adiabatic law

$$\frac{p}{\rho^\gamma} = \text{constant} = \frac{p_0}{\rho_0^\gamma},$$

where p_0 is the initial pressure, and γ is the ratio of the specific heat at constant pressure to that at constant volume. Thus the small pressure increment due to the wave can be found from

$$p = p_0 + (p - p_0) = \left(\frac{p_0}{\rho_0^\gamma}\right)\rho_0^\gamma(1 + s)^\gamma$$

$$= p_0\{1 + \gamma s + \gamma(\gamma - 1)s^2/2 + \cdots\},$$

or

$$p - p_0 = \gamma p_0 s\{1 + (\gamma - 1)s/2 + \cdots\}. \qquad (1.1.2)$$

To first order in the condensation, equations 1.1.1 and 1.1.2 can be combined to give the equation

$$\frac{(p - p_0)}{\gamma p_0} = s = -\frac{\partial \xi}{\partial x}. \qquad (1.1.3)$$

It is important to realize that p and ρ are the pressure and density of the layer of material *initially* at x. At time t this material has moved to the position $x + \xi$. Thus the expression $p(x, t)$ strictly means the pressure at time t of the material initially at x, and hence is the pressure at time t at the point $x + \xi$ in space, not at the point x.

As viscous forces and external forces are assumed to be absent or negligible, the motion of the mass of material is caused solely by the pressure* forces acting on it. Let $\eta = x + \xi$ denote the absolute position at time t of the layer initially at x. Then the forces on the element initially between x and $x + \delta x$ are $p(\eta)$ at η, and $p\{\eta + (\partial\eta/\partial x)\delta x\}$ at $\eta + (\partial\eta/\partial x)\delta x$. The resultant force is thus $-(\partial p/\partial\eta)(\partial\eta/\partial x)\delta x$, or $-(\partial p/\partial x)\delta x$. The mass of the element is $\rho_0\delta x$ and its acceleration is $\partial^2\xi/\partial t^2$.
The equation of motion of the element is therefore

$$\rho_0\delta x\,\frac{\partial^2\xi}{\partial t^2} = -\frac{\partial p}{\partial x}\,\delta x$$

or

$$\rho_0\,\frac{\partial^2\xi}{\partial t^2} = -\frac{\partial p}{\partial x}. \tag{1.1.4}$$

If the material was in a uniform condition before the arrival of the small disturbance, so that p_0 and ρ_0 are constants independent of x, then $\partial p/\partial x = \partial(p - p_0)/\partial x$, and equation 1.1.3 can be used to eliminate p from equation 1.1.4, giving

$$\frac{\partial^2\xi}{\partial t^2} = (\gamma p_0/\rho_0)\,\frac{\partial^2\xi}{\partial x^2}, \tag{1.1.5}$$

to first order. This is the wave equation in one space dimension.

The general solution of this equation is

$$\xi = \xi_+(x - a_0t) + \xi_-(x + a_0t), \tag{1.1.6}$$

where ξ_+ and ξ_- are arbitrary functions of the variables $x - a_0t$ and $x + a_0t$, respectively. The quantity $a_0 = \sqrt{\gamma p_0/\rho_0}$ is evidently the speed of sound, because $\xi = \xi_+(x - a_0t)$ represents a wave form travelling in the direction of increasing x at speed a_0 without change of shape, and $\xi = \xi_-(x + a_0t)$ similarly represents an unchanging wave form travelling at speed a_0 in the direction of decreasing x. In this way the analysis shows that small disturbances travel without change of form, and at a constant speed, a_0.

The velocity of the material particles in the layer, due to the disturbance caused by the passage of the wave, is $\partial\xi/\partial t + \dot{\xi}$. The particles themselves do not move at the speed of sound; only the wave form does. In

* 'Pressure' is used here in the sense of a general, internal normal stress.

acoustics the speed of sound in a material—fluid or solid—is often expressed in terms of the coefficient of volume elasticity of the material, κ (commonly called the 'bulk modulus'). This coefficient is defined as the ratio of the normal stress increment on an element of the material, δp, to the resulting change in volume of the element per unit volume, $\delta\rho/\rho$: that is,

$$\kappa = \frac{\delta p}{\delta\rho/\rho} = \frac{p - p_0}{s}, \tag{1.1.7}$$

for small pressure differences, $p - p_0$. This relationship is a form of Hooke's Law which asserts that stress is proportional to strain. In this case the strain is the volume strain, or condensation.

Thus the adiabatic law as given in equation 1.1.3, which can be written as $(p - p_0)/s = \gamma p_0$, is just a form of Hooke's Law, expressing the fact that the material is elastic and that its adiabatic bulk modulus is $\kappa_0 = \gamma p_0 = \rho_0 a_0^2$. The speed of sound in any elastic material conforming to Hooke's Law is evidently $a = \sqrt{\kappa/\rho}$. Thus the nature and propagation of small-amplitude, longitudinal, compressive waves are essentially the same in all elastic materials—gas, liquid or solid.

1.1.2 *Plane waves of finite amplitude*

If the condensation is not small then the wave does change form and does not travel at a constant speed. In such cases higher order terms in the adiabatic law, equation 1.1.2, cannot be neglected. To a second approximation in s this is

$$p - p_0 = \gamma p_0 s\left\{1 + \frac{(\gamma - 1)s}{2}\right\} = \rho_0 a_0^2 s\left\{1 + \frac{(\gamma - 1)s}{2}\right\}. \tag{1.1.8}$$

The expression for conservation of mass, $\rho_0\delta x = \delta_0(1 + s)(1 + \partial\xi/\partial x)\delta x$, gives exactly $s = -(1 + s)\partial\xi/\partial x$. Thus

$$\begin{aligned} p - p_0 &= -\rho_0 a_0^2 \frac{\partial\xi}{\partial x}(1 + s)\left\{1 + \frac{(\gamma - 1)s}{2}\right\} \\ &= -\delta_0 a_0^2 \frac{\partial\xi}{\partial x}\left\{1 + \frac{(\gamma + 1)s}{2}\right\}, \end{aligned}$$

to second order. The equation of motion now becomes

$$\rho_0 \frac{\partial^2\xi}{\partial t^2} = -\frac{\partial}{\partial x}(p - p_0) = \rho_0 a_0^2 \frac{\partial^2\xi}{\partial x^2}\left(1 + \frac{\gamma + 1}{2}s\right) + \rho_0 a_0^2 \frac{\gamma + 1}{2}\frac{\partial\xi}{\partial x}\frac{\partial s}{\partial x}.$$

Again, to second order $(\partial\xi/\partial x)(\partial s/\partial x) = (-s)(-\partial^2\xi/\partial x^2)$, so that finally, dividing both sides by ρ_0 and collecting terms gives

$$\frac{\partial^2\xi}{\partial t^2} = a_0^2\{1 + (\gamma + 1)s\}\frac{\partial^2\xi}{\partial x^2}. \tag{1.1.9}$$

As now $a_0^2\{1 + (\gamma + 1)s\}$ appears in place of a_0^2 as in (1.1.5) this equation shows that to this order of approximation the speed of propagation of the wave from particle to particle is $a_0\{1 + (\gamma + 1)s/2\}$ and is hence greater the greater the compression. The peaks of a pressure wave of initially sinusoidal form will move at a speed faster than a_0 and the troughs will move at a speed slower than a_0, so that the wave form tends to a saw tooth shape as shown in Fig. 1.2. The eventual steepness is determined by the

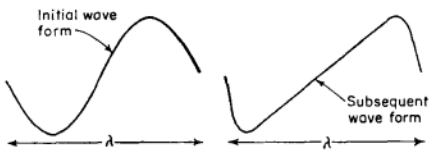

Fig. 1.2 Steepening of wave forms of finite amplitude.

rate of irreversible internal dissipation of energy characteristic of the material, which has not been considered here; for example, strong disturbances in gases may steepen up into shock waves[1].

1.1.3 *Intensity and energy in a plane travelling wave*

Travelling sound waves carry energy. Consider a wave of small amplitude travelling at speed a_0 in the direction of increasing x. The particle displacement is $\xi = \xi_+(x - a_0t)$. The particle velocity (which is also equal to the volume velocity across a surface of unit cross sectional area) is $\dot{\xi} = \partial\xi/\partial t = -a_0\xi'_+(x - a_0t)$, where the dash denotes differentiation with respect to the argument $x - a_0t$. The force per unit area on the material to the right of $x + \xi$ (exerted by the material to the left of $x + \xi$) is $p(x, t) = p_0 + (p - p_0)$. Using relationships obtained previously gives

$$p - p_0 = \rho_0 a_0^2 s = -\rho_0 a_0^2\frac{\partial\xi}{\partial x} = -\rho_0 a_0^2\xi'_+ = \rho_0 a_0\dot{\xi}. \tag{1.1.10}$$

This equation expresses the important result that the acoustic pressure in a plane, small-amplitude, travelling wave is proportional to the particle velocity in the direction of propagation. The constant of proportionality, $\rho_0 a_0$, is called the *characteristic specific acoustic resistance* of the material.