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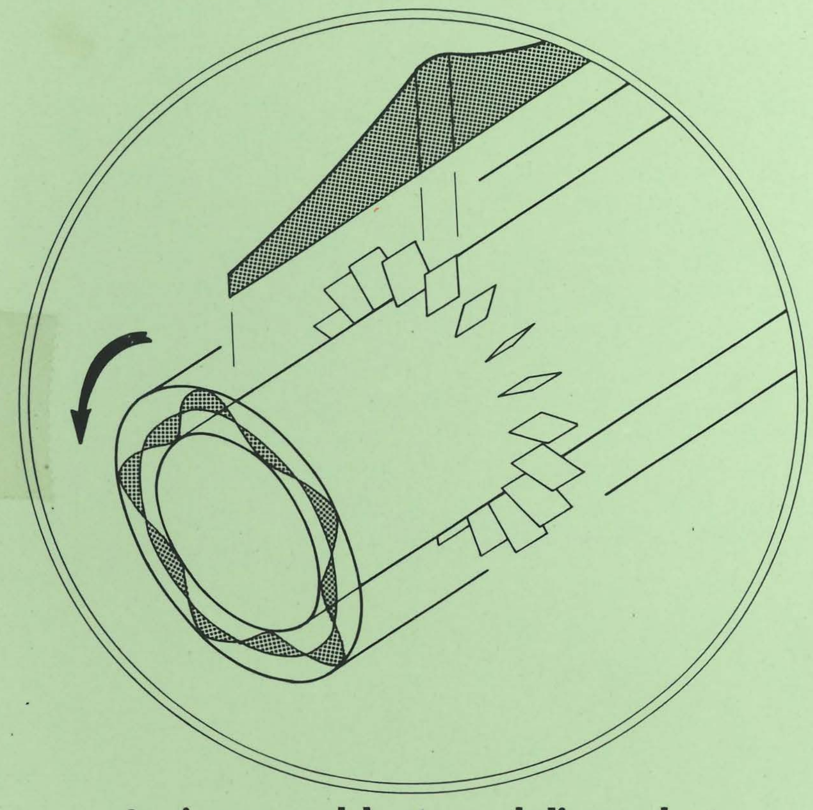
FROM POWER STATIONS TO AEROPLANES:
What do Mechanical Engineers do ?



An inaugural lecture delivered at the University College of Swansea on December 8, 1986

by

RALPH PARKER
D.Sc., C.Eng., F.I.Mech.E., M.R.Ae.S., F.I.O.A.
Professor of Mechanical Engineering

First published 1986 by University College of Swansea

Obtainable from the Registrar's Office,
University College of Swansea,
Singleton Park,
Swansea, SA2 8PP

ISBN 0 86076 119 3

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1. Introduction

The privilege of delivering a public lecture in the University is a unique opportunity to speak on a subject of ones own choosing, the only restriction being that it is should be of general interest. It seems logical therefore to start with a question which has often arisen in conversation with people not directly involved with engineering.

When I am introduced to someone as a Mechanical Engineer the response is often "What is a Mechanical Engineer ?" or "I don't really know what that means" or something similar. In some cases people seem to think that to be able to say that they know nothing about engineering is a mark of respectability. The fact that many people really do not know what Mechanical Engineers do is a cause for concern. This is particularly true in regard to people in positions of influence, either in commercial and financial decision making or, possibly more importantly, in education or career advice.

Apart from a need to explain what Mechanical Engineers do it is opportune to consider three supplementary questions:

Why don't more people know what Mechanical Engineers do?

Is there any connection between the present state of British industry and the apparent obscurity of Mechanical Engineers ?

How can the widespread claim to know little or nothing about engineering be consistent with the deluge of advice and criticism about the training of engineers which is offered by so many people ?

After briefly discussing what the words mean I propose to discuss some examples of Mechanical Engineering activity to give an insight into what some Mechanical Engineers do. They are examples of quite spectacular achievement which affect the every-day life of our community. In some cases projects would have been brought to fruition more quickly and efficiently if the technical training of the engineers responsible had been more complete than it was which suggests that the technical content of the training received by entrants to the profession should be increased. This is not consistent with the popular view that Engineering courses are too specialised and do not produce sufficient expertise in non-technical subjects which influence or are influenced by engineering activities.

The examples will inevitably reflect my own limited experience, interests and prejudices and I shall naturally take the opportunity to include the investigation of a problem which is currently affecting the design of high performance turbomachinery and will keep us occupied for a very considerable time.

2. What do the words "MECHANICAL ENGINEER" mean?

Unfortunately, use of the word "Engineer" is frequently misunderstood in a way that can cause much confusion and even resentment. At one time an "Engineer" was someone whose function required a relatively high level of professional responsibility for the technical, or "engineering science" content of his work. In a manufacturing company this was primarily design and development of the product or of equipment required to make the product. In a power station or on board ship it was someone with overall responsibility for operation at any given time, that is the shift or watch keeping engineer, in other cases it was the staff with technical responsibility for inspection and maintenance of plant. For the engineer to discharge his responsibilities he directed and depended on the work of others who described themselves as draughtsmen, fitters, machinists, engine drivers, mechanics, etc.. Over the years the word "engineer" has been used progressively more widely to include most of the above functions and also to include semi-skilled personnel trained to maintain certain specific items of domestic equipment. When the media refer to Engineers they often mean someone who, a few years ago, would have been described as a maintenance mechanic though in other cases they mean all the members of trade unions connected with the Engineering industry regardless of their actual functions! To make matters more confusing still, most new engineering designs are referred to as the work of "scientists".

Many professional engineers would like to prevent the word "Engineer" being used for anyone whose work does not require a knowledge of Engineering Science, that is, to exclude the application of practical skills of any kind. Such an idea is completely impractical. Apart from the difficulty of defining a rigid boundary, there is no authority with power to legislate effectively on what a word is to mean. This is true of any language like English which is the principal language in many countries. The word billion is an example of popular usage changing the meaning of a word, a "billion" used to be a million million but Americans started to use billion for a thousand million. There were occasional misunderstandings and some Americans were accused of exaggeration but when Mrs. Thatcher found that the American meaning sounded more impressive in political speeches the original meaning was doomed.

It is possible to "protect" a name or title against misuse with intent to deceive. We are all familiar with the protection given to various functions in the medical profession where anyone offering services by falsely claiming to be a qualified practitioner is committing a criminal offence. Titles such as "chartered accountant", and "chartered surveyor" have similar protection. In all such cases the title is awarded by a body holding a Royal Charter which specifies what titles it is entitled to award and this form of protection has recently been established for all branches of Engineering through the "Engineering Council" which was set up following publication of the Finniston Report*

The position as stated by the Engineering Council is therefore as follows:

* *"Engineering Our Future. Report of the Committee of Enquiry into the Engineering Profession", chairman Sir Montague Finniston, F.R.S. Cmnd 7794, January, 1980.*

i. There is no protection for the title "Engineer".

ii. The title "Chartered Engineer" together with its abbreviation "C.Eng." is protected by virtue of the Engineering Council's Charter.

iii. "Chartered Mechanical Engineer" can be used by Corporate Members of the Institution of Mechanical Engineers, but no abbreviation is allowed. The Charter of the Institution of Mechanical Engineers does protect the abbreviations "FIMechE" and "MIMechE" and these latter two abbreviations could be used with "Chartered Mechanical Engineer".

The Engineering Council maintains an official list of Chartered Engineers but the power to grant Chartered Engineer status is delegated to fifteen Institutions of which the Institution of Mechanical Engineers is one of the largest.

Whatever titles people use, every project is a team effort and success depends on the skills and knowledge of every member of the team, some of whom may contribute more than the person with overall responsibility. In general, overall supervision of a project and the application of scientific knowledge are the responsibilities of Chartered Engineers and there is no reason why the other contributors should not call themselves "Engineers" provided they do not assume responsibilities which they are not competent to discharge. This is really the most important point, in all engineering activities failure of an item of plant always involves a financial loss but in some cases can be catastrophic and may lead to serious injuries and loss of life.

In some cases the word "MECHANICAL" causes more difficulty than "ENGINEER". To most people the word has two possible meanings, one is "of machines or mechanisms" and the other is "like a machine, automatic, lacking originality" (amongst other definitions in The Concise Oxford Dictionary). These are both inadequate for the present purpose. Mechanical Engineers are generally concerned with machinery in which energy is converted from one form to another or is used to achieve some desired result such a cutting or forming materials. This includes all "prime movers" in which natural sources of energy such as combustible fuels, nuclear fission, hydro power and wind or tidal energy are used to produce mechanical energy, generally in the form of a rotating shaft. The energy may be transmitted directly through shafts or converted further into electrical, hydraulic or pneumatic power for transmission and distribution before being used to drive other mechanical systems, provide heat and light, etc. Mechanical systems which utilise the energy include virtually all manufacturing processes, food processing, all forms of transport and materials moving equipment, pumps, fans, packaging machines, etc. Preparation of a complete list is impossible, it would cover practically every activity in the civilised world from building reservoirs to recording pop music or from building nuclear submarines to providing micro-manipulators for surgical use.

3. Power station plant and Mechanical Engineering

The generation of electrical power for domestic and industrial use started with reciprocating steam engines (previously used to drive textile mills and other factories directly) coupled to a multitude of different types of generator. Since the beginning of this century steam turbines have replaced the reciprocating engines and power stations now employ an almost standard system of large, high pressure steam turbines driving A.C. generators or "alternators" backed up by gas turbines driving small alternators. Electrical power generation obviously requires electrical engineers but, in fact, the design of turbines and many other major items of plant requires more mechanical than electrical expertise, for example fuel handling, boilers, pumps, fans and even the alternators themselves.

Figure 1 shows one type of turbo generator built by the Brush Electrical Engineering Co. of Loughborough. and installed in the Tir John Power Station in Swansea. The largest unit installed in the U.K. was rated at 50MW. and the blades from one of the 40MW Swansea units (on which I worked during my early training) is now in the Maritime and Industrial Museum after a useful service life of over 30 years. The special feature of the Ljungstrom turbine was that the blades were mounted in concentric rings attached alternately to two discs which rotated in opposite directions driving two separate alternators. This had a number of advantages over conventional axial-flow designs for small capacity machines but major vibration problems were encountered with the large units and many fatigue failures occurred in sets of 30 MW and above (several in the Swansea sets). The problems involved vibration waves travelling round the discs and rings at different frequencies according to whether they moved with or against the shaft rotation. At the time, the frequencies could not be predicted accurately but a new design developed jointly by Brush and Siemens Schuckert solved the problem and existing machines were rebladed though it was obvious that expansion to larger sizes would be difficult.

The formation of the C.E.G.B. after the second world war resulted in a series of standard specifications for equipment in U.K. power stations. Unit outputs of 30 and 60 MW were specified for turbine generator sets which reflected the state of technology at the time. The output of turbo-alternators was limited for several years by the mechanical design of the alternators. Electrical Engineers can design the basic magnetic and electrical components for almost any output but mechanical considerations such as the stresses in the rotor and the danger of unacceptable vibration limit the maximum dimensions. Heat is generated due to electrical resistance in the conductors forming the windings and by hysteresis losses due to the alternating magnetic flux in the iron core. The need to remove this heat limited the maximum output which could be generated in a given size of machine. The efficiency of alternators is very high but two percent of the output of a 60 MW machine is equivalent to 1200 one kW heaters and most of the heat was conveyed by conduction through the electrical insulation to the iron before that was, in turn, cooled by air or hydrogen.

Design refinement brought slow advances up to 100 MW until, in the late 1950s, "direct cooling" was developed. The electrical conductors were made hollow and compressed hydrogen and de-mineralised water were passed through the bores in the rotors and stators respectively. With this arrangement heat was removed directly from the conductors instead of depending on conduction through the insulation. Compressed hydrogen was also used to cool the magnetic iron core. These developments allowed greatly increased outputs to be achieved with little or no increase in physical size and the alternator ceased to limit the unit output. A hydrogen compressor or blower is required for every alternator and the derivation of satisfactory designs for these from gas turbine compressor technology will be discussed later.

When the alternator ceased to limit the unit output, steam turbines developed rapidly and, although special types such as the Ljungstrom turbine could not compete, axial-flow machines using several cylinders and working at high steam pressures and temperatures were designed. By the mid 1960s machines with ratings of over 600 MW were being ordered, an impression of the physical size and complexity of the resulting units may be obtained from Figure 2.

Shaft and blade vibration are dominant considerations in the design of all turbines but failures are now rare. Power station engineering is not looked on as a very glamorous occupation and is rarely mentioned by the media apart from the effects of pollution. Power stations are however essential assets in every industrial community, they take between five and eight years to build and have an expected life of between 30 and 40 years without replacement of major plant items so reliability must be high. The units are too large for the building and testing of prototypes as is normal in many other industries so, with these constraints an advance in design which achieved a tenfold increase in the unit output in a period of less than 20 years was a notable achievement. Incidentally, this development took place exclusively in the U.K. where geographical and industrial factors created a demand for large sets in advance of other countries. At present there has been little demand for new power stations for several years and the capacity to build them has declined, if no new power stations are ordered soon the U.K. turbine generator industry will virtually cease to exist and plant will have to be bought from overseas when our present stations have to be replaced or expansion is required. This is not the sort of industry which can be created to meet a short term requirement for reasons which can not be assessed adequately in financial terms and therefore do not feature in formulating commercial and political policies.

4. Gas Turbines

At the same time as large steam turbines and alternators were being designed and developed, the achievements of Sir Frank Whittle and his team at "Power Jets" in developing practical jet engines for aircraft propulsion stimulated the development of many forms of gas turbine for aeronautical, marine and industrial use. The National Gas Turbine Establishment was formed by combining Power Jets and the Engine Department of the Royal Aircraft Establishment who had, for several years, been developing axial flow compressors in which the mean direction of air flow is parallel to the axis of the machine while Power Jets had made rapid progress using radial flow compressors in which the mean flow is radially outward.

N.G.T.E. supported industry in all the gas turbine projects but the main internal research and development effort was directed towards improving the efficiency, reliability and power/weight ratios of aero-engines and three sections dealt with compressors, combustion and turbines respectively. In the compressor section the axial flow design was the main line of development and the passing years have shown that this was the right choice for all except the smallest engines although it was a source of bitter disagreement in the early years. The research was divided into two areas, one was the development of high efficiency blade designs which achieved the maximum possible compression in each stage and the other was the elimination of serious blade vibration which was soon found to be one of the most important aspects of engine design.

All gas turbine aero-engines and most other practical gas turbine systems use air as the "working fluid" and use the oxygen in the air to burn the fuel, this is called an "open cycle" because the air can not be recirculated (as it would not support further combustion) and has to be discharged at the end of the cycle and replaced with a fresh supply.

For a stationary gas turbine, air is drawn in at the ambient conditions but when an aircraft is in flight the air entering the engines is compressed by the "ram" effect of the forward motion, the amount of compression depending on the ratio of the flight speed to the speed of sound, generally referred to as the "Mach Number". As the air is accelerated to the speed of the aircraft there is a reaction equal to the rate of increase of momentum which may be described as an "intake drag" force. In all cases the air entering the engine passes through a compressor to raise the pressure, through a combustion chamber in which it is heated and a turbine in which it is expanded to provide the power required to drive the compressor. The heating takes place at a constant pressure so, after compression and before expansion, the volume is increased approximately in proportion to the absolute temperature. The amount of energy absorbed when a gas is compressed or released when it is expanded through a turbine can be calculated from the volume flow (taking account of the progressive change in density) and the pressure change. Because the volume is greater when the hot air expands than when it was compressed, the pressure of the air leaving the turbine is above the surrounding atmospheric pressure, the difference depending on the amount of fuel burnt in the intervening combustion chamber.

The part of the engine described so far, often referred to as the "Gas generator", is illustrated diagramatically in Figure 3. The narrowing passage represents compression in the compressor and the diverging passage expansion in the turbine with the shaded area representing the mechanical connection between the compressor and turbine shafts. The "gas generator" may be followed by any one of several different devices in which the hot pressurised gas is expanded to the ambient pressure to produce the useful output.

Figure 4 shows a simple "jet engine" in which the gas from the gas generator is expanded in a nozzle or "jet pipe" and discharged backwards at high velocity creating a reaction or "thrust" on the aircraft. (The mechanism is the same as when a blown up baloon escapes before the neck is sealed.) The net force driving the aircraft is the jet thrust minus the intake drag.

In a stationary gas turbine used to generate power, drive pumps, etc., or for marine use, the gas generator is usually followed by a further turbine driving the load through a shaft as shown in Figure 5. In some cases a gear box is required as the optimum turbine speed is not always suitable for the driven machine.

The modern aero-engine is a complex combination of these concepts designed to produce the most efficient machine possible. Figure 6 shows the arrangement of a "by-pass" engine similar to the Rolls-Royce RB211 which is used to power large transport aircraft such as Jumbo-jets. The turbine is split into three sections, all free to run at different speeds. The first two drive two compressors while the third drives the large frontal fan. The air from the turbine then discharges to atmosphere as a hot jet surrounded

by a cold jet of air coming from the fan via a duct outside the "core engine". Both air streams contribute to the thrust and the proportions of the total thrust from each can be designed to achieve the required thrust at each stage of a flight with the minimum total fuel consumption. An engine designed for low aircraft speed will have a large proportion of the air passing through the bypass duct and low jet velocity while, for high flight speeds the velocities increase and the proportion of the flow through the by-pàss decreases. All the air entering the engine passes through the fan so the part entering the core engine is actually compressed in three sections.

The evolution of the present engine from the early, relatively simple, jets has been dominated by the fact that the power/weight ratio and the overall efficiency depend on the maximum temperatures which can be used safely and, for any maximum temperature, there is an optimum pressure ratio, which increases with the temperature. The maximum temperatures have increased progressively as new materials have been developed and also because techniques have been developed for cooling turbine blades with air drawn off the compressor and fed through passages in the blades to emerge through holes and form a cool layer between the hot gas and the actual metal.

Figure 7 is a cut away picture of one version of the Rolls-Royce RB211 engine and, although it is rather detailed, the fan, bypass duct and the two compressors followed by the combustion chamber and three turbines can be seen. The shafts connecting the turbines to the compressors are concentric tubes with ball and roller bearings supporting them inside each other. Each compressor has several rows of blades, alternate rows being mounted on the rotor and stator respectively. The inlet to the first rotor of each section is controlled by Inlet Guide Vanes which turn the air to flow in the required direction. One rotor row and one stator row comprise a "stage" although stages cannot be designed separately because the inlet to each rotor depends on the velocity and flow direction of the air leaving the stator of the preceding stage.

The compression process may be split up in different ways, Figure 8 shows a two shaft arrangement with some compressor stages on the same shaft as the fan. In this case the compressor design has been made more difficult but the basic mechanical arrangement has been simplified giving a saving in weight. This is an example of the sort of compromise all engineers have to make in the quest for reliable, efficient and economical machines.

Whatever arrangement is adopted, the main engine control is the rate at which fuel is delivered to the combustion chambers and the speed of each shaft automatically adjusts itself to the value at which the power produced by the turbine matches the power consumed by the compressor or fan on the same shaft. The result is that the compressor speeds vary over a wide range with associated changes in the pressure ratio (delivery pressure/intake pressure) and the rise in air temperature.

It is not too difficult to build a compressor to run efficiently and reliably at a constant speed but, speed variations are unavoidable and the compressor designer has to design the blades for high efficiency at one speed and then ensure that the compressor will continue to function satisfactorily at others. If the pressure ratios in the early stages are different from the design values the volume of gas reaching the later stages is affected and the compressor stages are said to be "mismatched", when this happens the performance of the whole compressor is affected. At speeds below design, the early stages actually operate with low axial velocities which causes the blades to be overloaded and can cause vibration. For speeds at which continuous operation is required it is important to minimise the effects of mismatching while for the lower end of the speed range, in which an engine will only be operated for short periods, efficiency is not important but it is essential that blade vibrations do not reach amplitudes at which the blades will fatigue.

The earliest engines operated with pressure ratios less than five and, in the 1950s, engines with axial flow compressors giving pressure ratios of the order of eight were in use. When this was increased blade vibration increased and problems such as compressor surge, arose. It was known that the problems were associated with stage matching and various methods of alleviating the problem have been developed.

If it was practical to have each stage on a separate shaft with its own turbine the problem of matching the stages would be relatively simple but the mechanical design would be a daunting task and it is hardly likely that a practical machine would result. One way of dealing with stage matching which is used extensively is called "variable geometry", mechanisms are provided to rotate the stationary blades of the early stages to compensate for the variation in axial velocity at off design speeds. The penalty is the weight and cost of the mechanism to rotate the blades and a control system to operate the actuators according to a predetermined "schedule" in relation to the speed. Yet another way to alleviate the problem is to provide "blow-off" valves at intervals along the compressor which release air to atmosphere and increase the flow in the early stages. In some engines a single compressor is used with variable geometry on several stages and a number of blow-off valves while on others the compressor is split into sections, as in the RB 211, so that the number of variable geometry and blow-off stages may be kept to a minimum or eliminated altogether. When the matching problem is not solved satisfactorily the compressor may "surge" producing major flow fluctuations which interfere with combustion and can cause rapid mechanical failure. In less severe cases the compressor may appear to operate satisfactorily but with the blades vibrating sufficiently to cause fatigue and eventual failure, the various sources which can excite blade vibration must therefore be considered.

5. Sources of vibration

One source of vibration referred to as "blade row interaction" is not related to stage matching. The effect of adjacent blade rows passing each other is to produce fluctuating forces on each blade at a frequency equal to the rotational speed multiplied by the number of blades in the adjacent row. Many failures due to blade row interaction were experienced in the earliest steam turbines so it was no surprise that similar excitation occurred in compressors. Avoidance of coincidence with the blade natural frequencies can be achieved by suitable design but can be difficult when operation over wide ranges of speed is required.

Vibration at off design speeds which can not be related to blade passing frequencies is almost always associated with mismatching and, by implication, with conditions in which the blades do not operate in the conditions for which they were designed.

A compressor blade functions very much like an aeroplane wing, it is placed so that the air passing each side is forced to change direction and leaves with a component of velocity at right angles to it's original

velocity as shown in Figure 9. The air passing underneath is bound to turn because the blade provides a positive barrier but the air passing over the upper surface will only flow along the surface if the amount of turning is not too great. If the incoming air approaches at too steep an angle as shown in Figure 10, the flow over the upper surface separates and a bubble forms. When this happens the mean air deflection is reduced and the lift, which is proportional to the rate of change of momentum, falls. The fluid in the bubble tends to rotate forming a vortex which may be swept downstream to allow another to form in its place. The formation and shedding of vortices causes the separation point to oscillate along the surface generating corresponding variations in the blade lift.

The flow separation from the upper surface is referred to as "stall". I do not expect many people have experienced an aircraft stall but I can assure you that the most notable feature is a feeling that something is wrong and the wings are no longer supporting the aeroplane. The effect in a compressor is that the amount of energy transferred to the air is reduced. It does not generally happen simultaneously along the whole blade row, some blades cease to deflect the air to the required angle while others continue to function normally. This produces a redistribution of the air flow so that it no longer passes uniformly through the whole of the annulus containing the blades. Some regions pass very little air while others operate more or less normally, the regions with little or no flow rotate round the annulus in the direction of rotor rotation and both rotor and stator blades are subject to abrupt changes in the lift force as they enter and leave the stalled region, or "stall cell". This causes vibration in the same way as hitting the blades repeatedly with a soft hammer. At very low speeds the impacts may be acceptable but generally the only cure is to alter the aerodynamic design to reduce the stall.

In some cases the blades do not stall completely but the flow separates part way along the suction surface and, for a small increase in inlet flow angle (incidence) the separation moves forwards causing the lift to decrease instead of increase as it would if there were no separation. This creates an unstable situation as bending motion of a blade causes a change in incidence and the blades "flutter". This is another problem which used to arise with aircraft wings and caused many failures in the early days of flying. In the compressor mechanical and acoustic coupling between blades complicates the mathematics of flutter prediction but it is fair to say that the problem is now well understood and flutter problems which may arise in research or development compressors can generally be recognised and eliminated by changes to the aerodynamic design or adjustment of the blade natural vibration frequencies.

In the last ten years or so a further source of blade vibration has been identified in advanced aero-engine research compressors. Before discussing this it is necessary to return to power station engineering as there has been a considerable interaction between the technologies. Aero-engine technology has contributed to power station plant design and a major failure in a power station in 1963 stimulated research in the University which provided the basis for identifying the source of the current aero-engine problem.

6. Gas circulators

The Gas Turbine Department of the English Electric Co. Ltd., besides building industrial gas turbines, was a subcontractor to other divisions of the company for the design and supply of

i. The main carbon dioxide gas (CO_2) circulators for nuclear power stations

and

ii. Hydrogen circulators for direct cooled alternators which were mentioned earlier.

The CO_2 circulators were large diameter single stage machines connected to the reactor and boilers by large gas ducts while the hydrogen circulators were three and four stage compressors which became integral parts of the alternators. Neither bears any obvious resemblance to an aero-engine although the basic designs used the technology developed at NGTE and in the aero-engine companies. In both cases very satisfactory results were achieved as regards efficiency and reliability albeit with a major vibration failure of the first CO_2 circulators on the way. This occurred in the Hinkley Point "A" power station in Somerset.

Figure 11 shows the layout of the reactor and one of the six associated loops comprising boiler, gas circulator and connecting ducts. The CO_2 passes up through the reactor collecting heat and down through the boiler where it passes over the outside of the tubes providing the heat to convert water into superheated steam. The circulators are required to raise the pressure of the gas enough to restore the pressure losses due to flow resistance in the reactor, ducts and boiler. In all gas cooled reactors the circulators use about ten percent of the total power generated. The specified performance of the Hinkley Point A circulators when running at the design speed was a gas flow rate of approximately 3/4 ton of CO_2 per second at gas conditions of 7.5 atmospheres pressure and nearly 200°C. This gives a gas density of over 10 times the density of air at sea level. The pressure rise was approximately half an atmosphere and the power requirement was estimated to be 6250 H.P. or 4660 kW. The circulator is inside a casing 12 ft (3.65 m) in diameter and the maximum shaft speed is 3000 R.P.M., flow control being effected by varying the speed of a special turbo-alternator supplying all six circulators on one reactor.

The original design is shown in Figure 12, the blading design was based on methods used for axial flow fans and took little or no account of the available axial-flow compressor technology. Furthermore no consideration was given to noise generation or the possibility that noise and vibration due to blade row interaction might be transmitted to components other than the blades, either acoustically or through the structure. Fans can be very noisy when operating in normal atmospheric conditions if no precautions are taken and the problem increases if the density of the working fluid (gas) is increased. A half scale model using air at atmospheric pressure and driven by a 200 H.P. (150 kW.) motor was used to check the performance. This emitted a clear, high pitched whistle which could be heard easily a mile away. As is usual with this type of machine, there were no full scale prototypes and each production machine was tested in a facility using a 700 H.P. (522kW.) motor in the works in Rugby. The first run brought an immediate complaint about the noise from the trade unions. Testing during the day was stopped but continued in the evenings and a deluge of complaints from the town followed so testing had to stop until the problem was overcome. This was achieved by spending a large amount of money on sound insulation to contain the noise within the test facility. The motors for operation at site were rated at 7000 H.P. (522 kW.). As soon as commissioning started it was found that, in spite of the thick pressure casings, thermal insulation and concrete shield walls the noise levels were unacceptable in areas occupied by operating personnel.

Negotiations were started about the cost of sound proofing the blower houses.

At that point it should have been realised that there were very large pressure fluctuations inside the machine and that serious vibration would result. Six machines had been accepted and were running as part of the commissioning programme on the first reactor when the flow in one circuit started to fall and the driving motor began to absorb less power than it should. Each circulator had completed a total of about 1200 hours (50 days) operation at full speed, and they were running on a six week, non stop reactor test which was about half completed. The external indications of a serious failure were obvious but commercial considerations dictated that all six machines must run for six weeks without stopping. A few days later the evidence of failure was beyond question with performance deteriorating on several machines so they were all stopped after a great deal of secondary damage had been added to the original failures.

Fatigue was well advanced in practically every component of the circulators and in the associated ducting, there were large holes in the diffuser walls (Fig 13a) which explained the loss of performance and debris from the diffusers had done a lot of damage to the blading (Fig 13b). In one case one of the Inlet Guide Vanes (the first row of stationary blades) had broken away at both ends and become lodged against another vane. Where they were in contact, metal had disappeared from both vanes and they became interlocked by about 6 cm.(Fig. 13c).

It is fortunate that the diffusers failed when they did, otherwise there would have been no external indication until other components failed which would probably have been after the reactor was loaded with fuel and made critical, if that had happened there would have been a radiation problem to deal with before the extent and cause of the failure could be investigated.

Naturally, the failure triggered off an intensive experimental programme to develop a cure as quickly as possible. It also stimulated reviews of the design of gas circulators for other nuclear power stations and led to the addition of instrumentation to detect acoustic and mechanical sources which could possibly have similar consequences. The long term effect was to highlight the importance of pressure fluctuations in turbomachinery and the inadequacy of the technology in use at the time.

The circulators on the second reactor had done very little running and were undamaged so investigations started almost immediately. Pressure fluctuations at twice the rotor blade passing frequency were measured with sound pressure levels over 170 dB in the inlet and outled ducts. Such levels were almost unknown and are compared with familiar sounds in Figure 15.

The pressure fluctuations literally shook the stationary blades and other components of the circulator to pieces. The source was blade row interaction which has already been mentioned but, in this case, it did not coincide with a blade resonance. The problem was cured by removing the IGVs and, with some further related modifications to improve the flow distribution, all twelve machines (two reactors) were rebuilt. Figure 14a shows the modified cross section and Figure 14b is a general view in which the rotor blades and a flow straightener grid may be seen. The modified circulators have now operated satisfactorily for over twenty years.

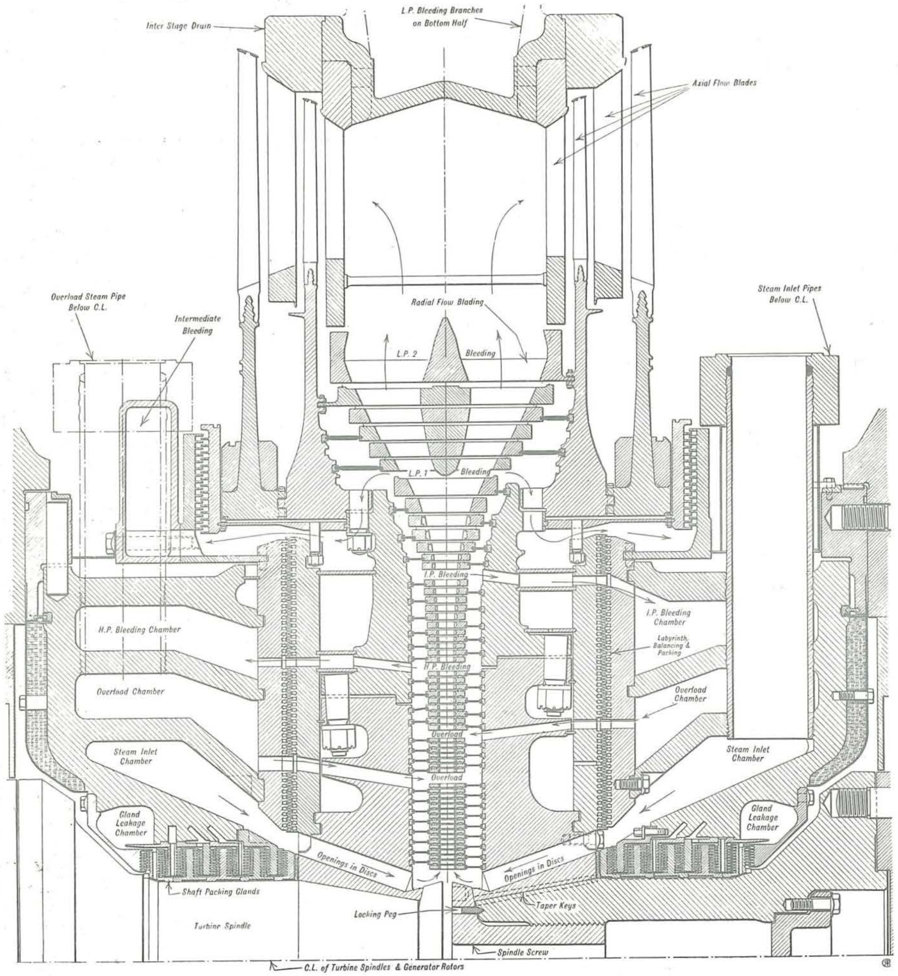


Fig 1. Ljungstrom turbine

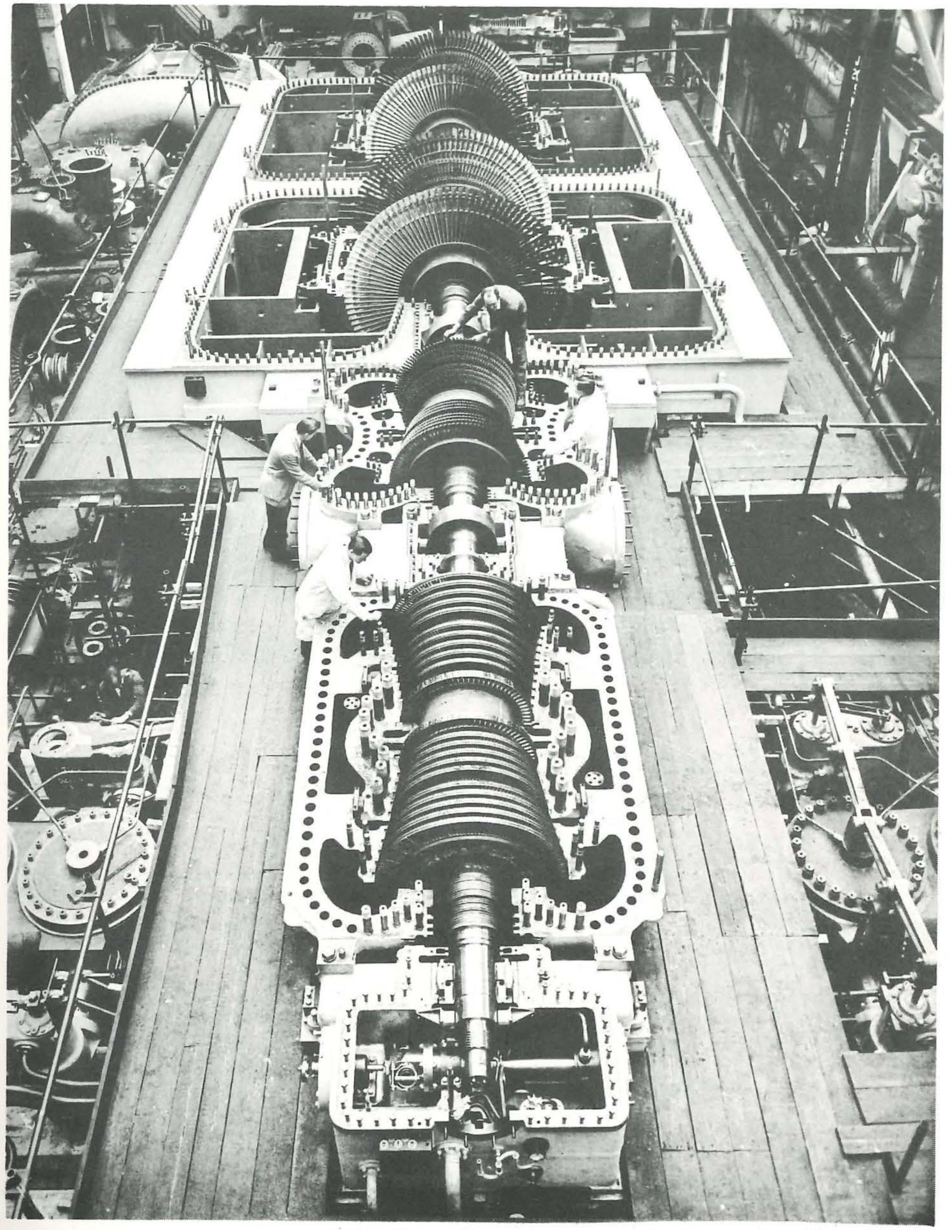
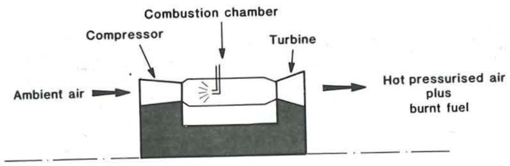
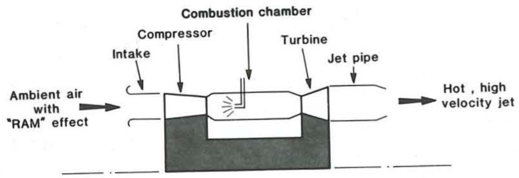


Fig 2. 500 MW turbo alternator set



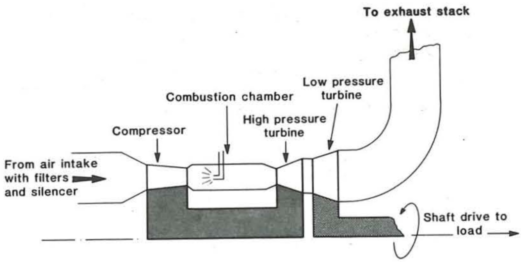
THE BASIC GAS GENERATOR OF A GAS TURBINE

Fig 3. Gas generator part of a GT



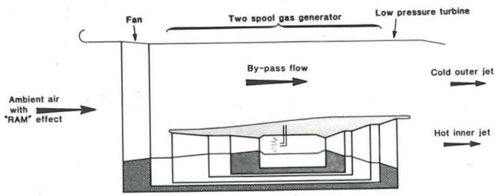
SIMPLE JET ENGINE

Fig 4. Simple jet engine



TWO SHAFT , POWER PRODUCING GAS TURBINE

Fig 5. Simple engine with power turbine



THREE SHAFT , FRONT FAN BY-PASS ENGINE

Fig 6. Three spool by-pass engine

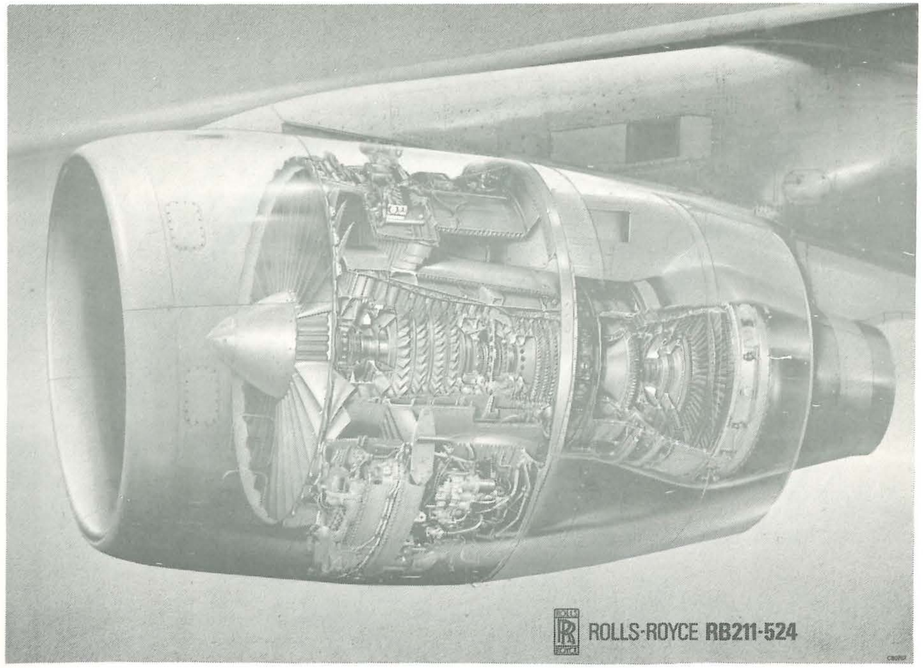
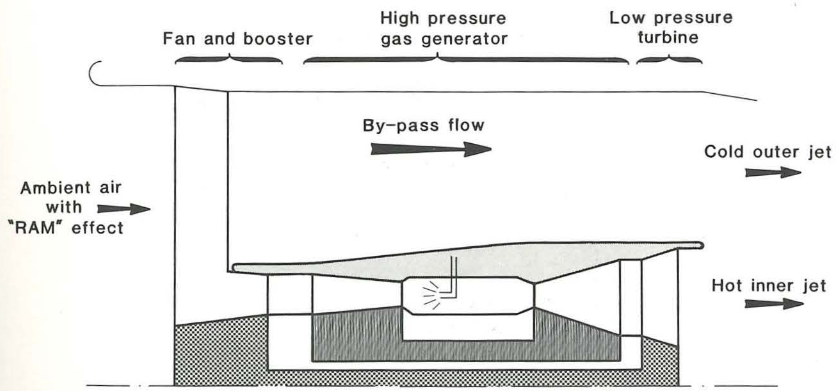
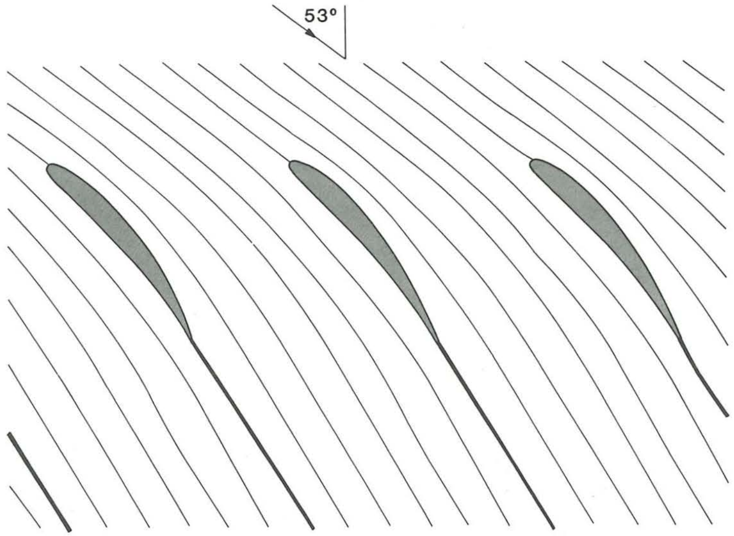


Fig 7. RB 211-524 cut-away picture



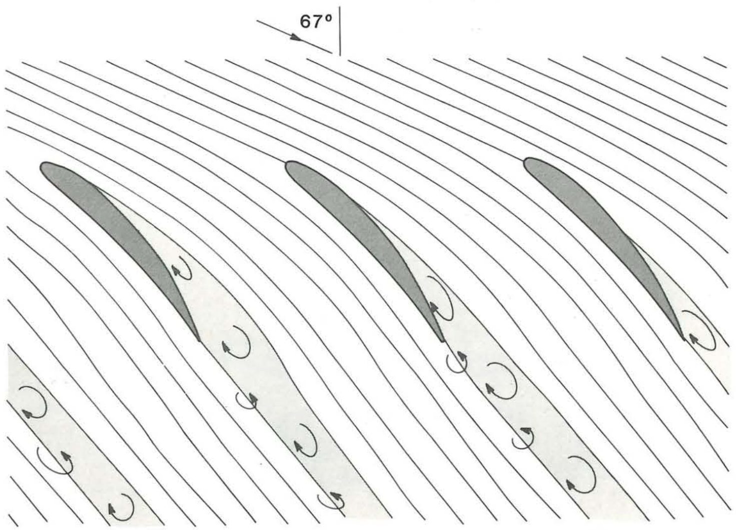
TWO SHAFT , FRONT FAN BY-PASS ENGINE

Fig 8. Two spool by-pass engine



FLOW THROUGH A CASCADE OF BLADES AT "DESIGN" INCIDENCE

Fig 9. Unstalled cascade



FLOW THROUGH A CASCADE OF BLADES
AT INCIDENCE ABOVE STALLING

Fig 10 Stalled cascade

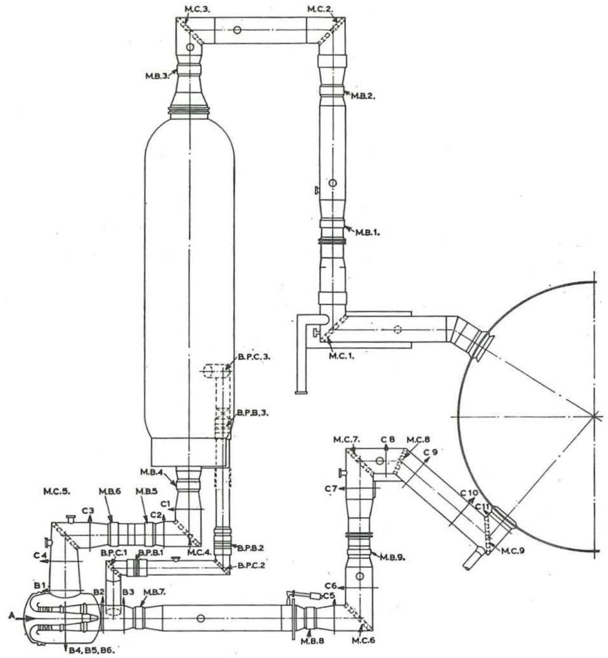


Fig 11 Reactor loop

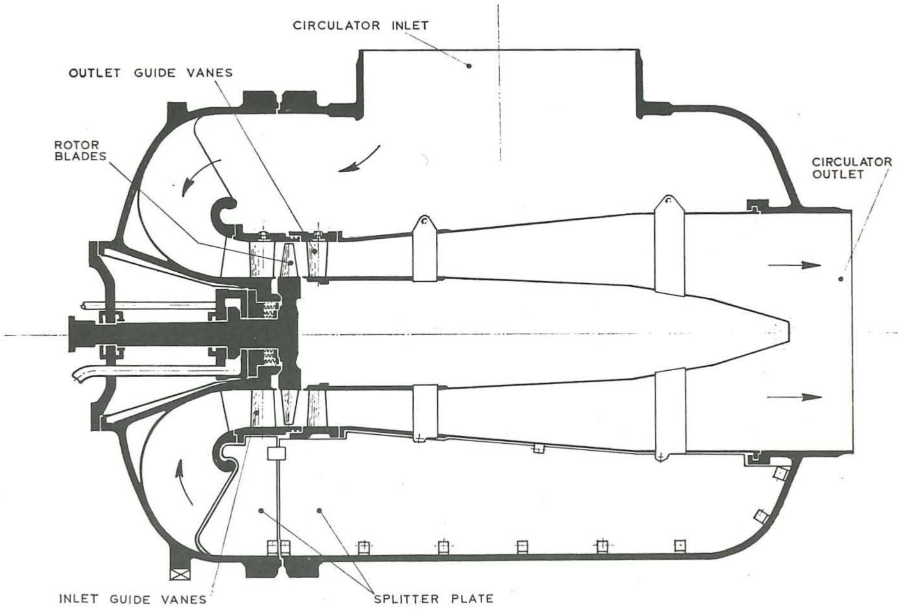


Fig 12 Circulators, original design

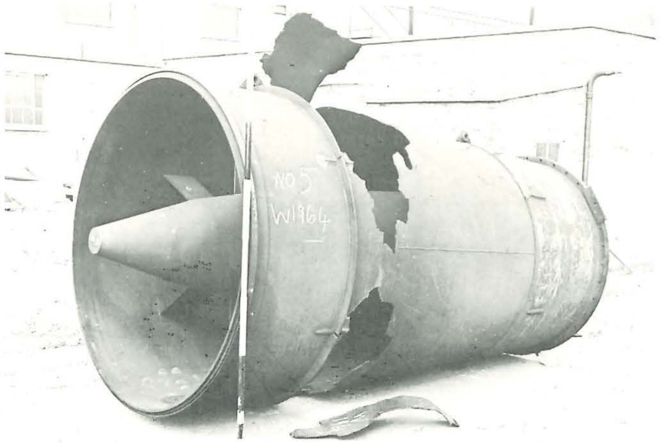


Fig 13a

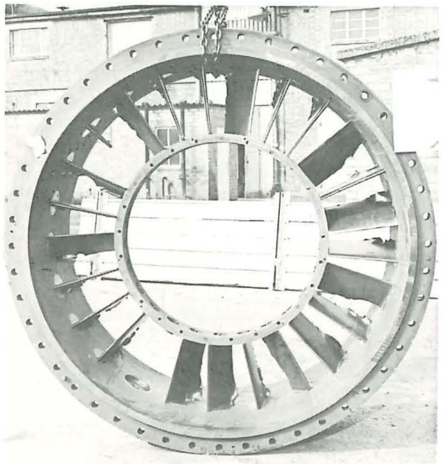


Fig 13b

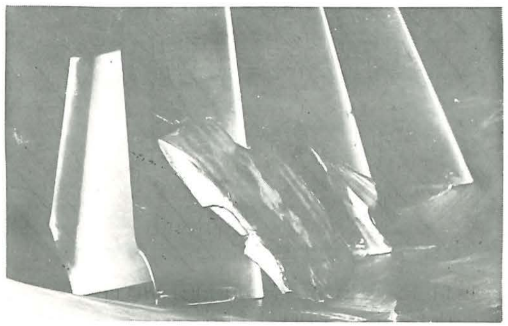


Fig 13c   Damage to diffuser, blading.

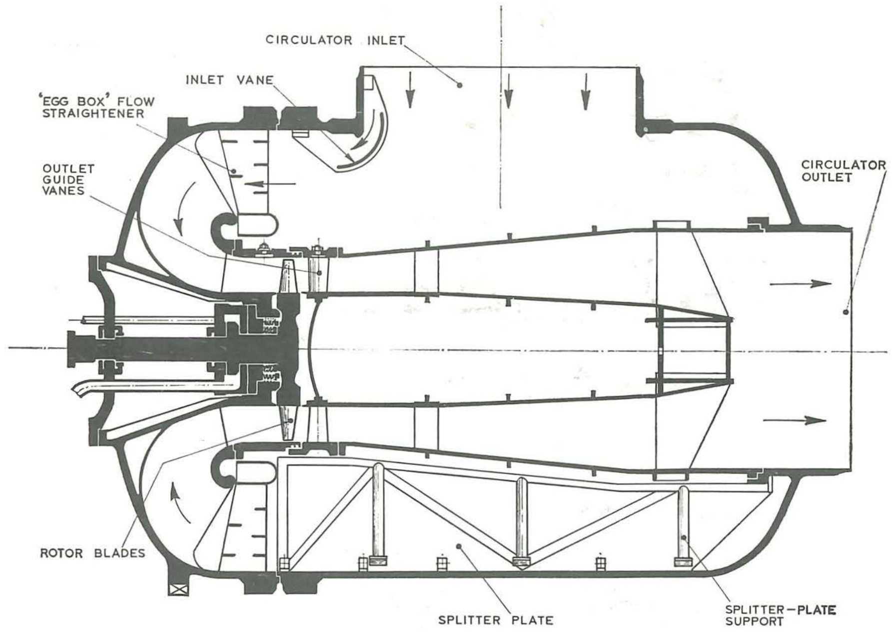


Fig 14a

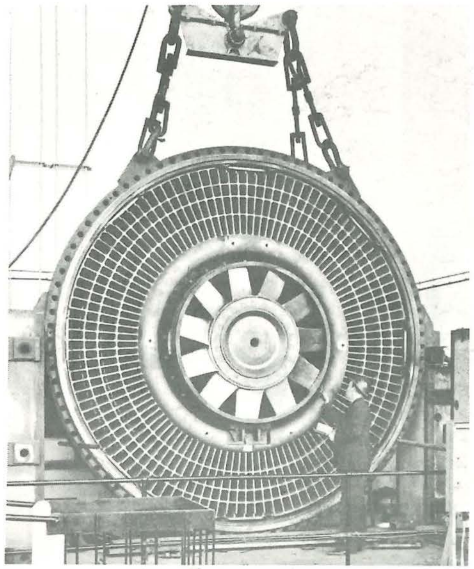
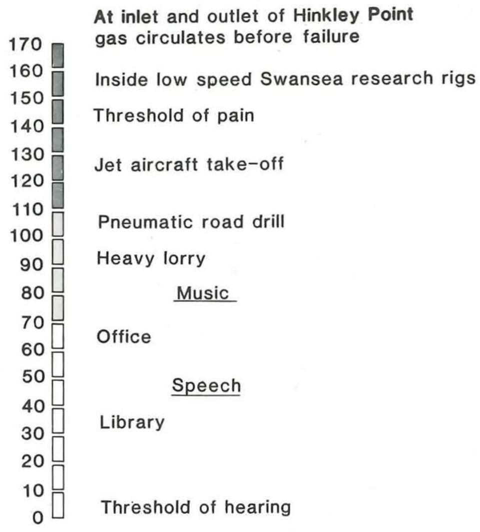
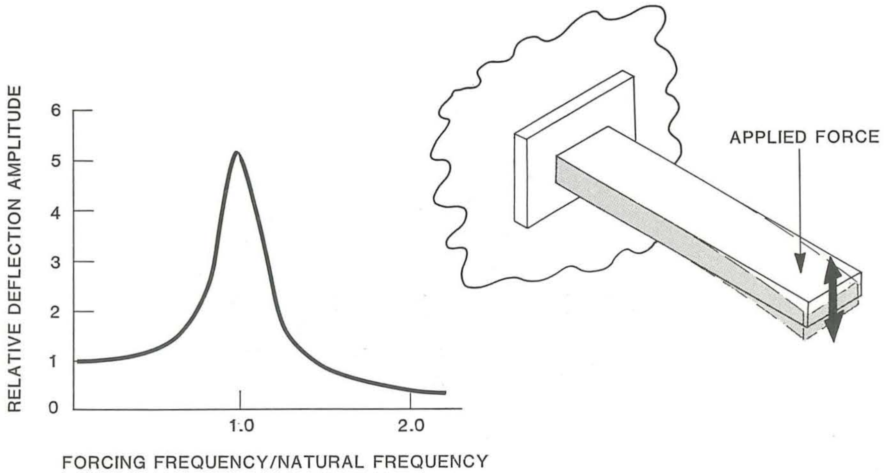


Fig 14b   Modified circulator



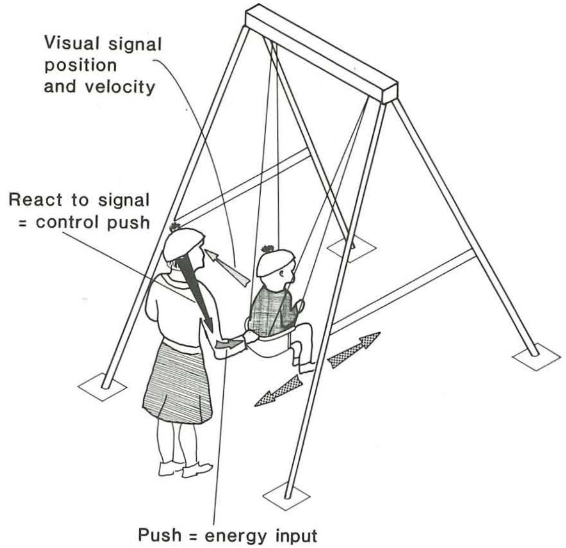
SOUND PRESSURE LEVELS IN DECIBELS

Fig 15 S.P.L. slide



VIBRATION AMPLITUDE WITH VARIATION OF FORCING FREQUENCY

Fig 16 Cantilever and response curve



SELF INDUCED OSCILLATION AT NATURAL FREQUENCY

Fig 17 Child on swing

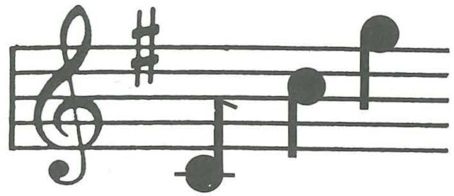
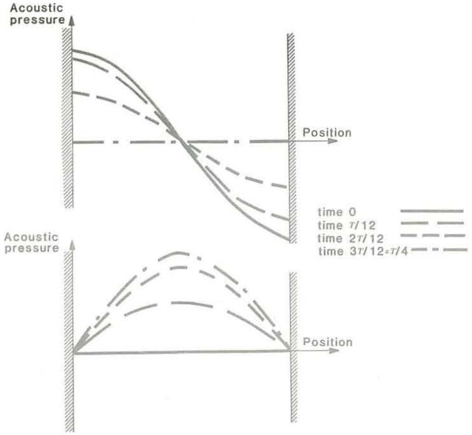
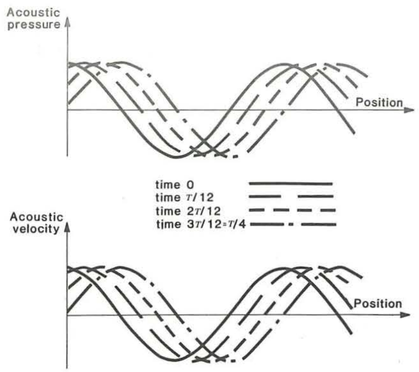


Fig 18 Musical staff (C,C,G,)



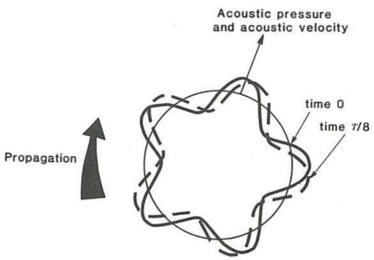
A STANDING WAVE IN A STRAIGHT PIPE WITH CLOSED ENDS - RESONANCE

Fig 19 Standing wave



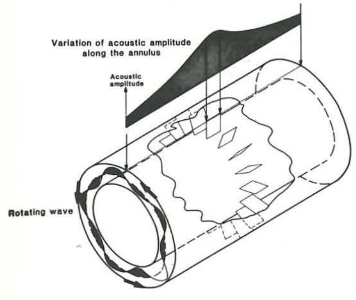
A 'TRAVELLING' WAVE

Fig 20 Travelling wave



A TRAVELLING WAVE IN A CIRCULAR LOOP-RESONANCE

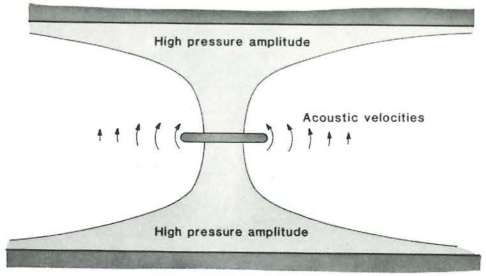
Fig 21 Resonance in a circular loop



ACOUSTIC RESONANCE IN AN ANNULAR SPACE CONTAINING A CASCADE OF FLAT PLATES

Fig 22

Resonance in an annulus with a cascade



SINGLE PLATE IN A PARALLEL PASSAGE : THE FIRST ACOUSTIC MODE

Fig 23 Beta mode resonance

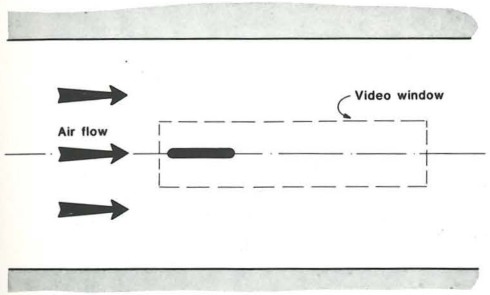
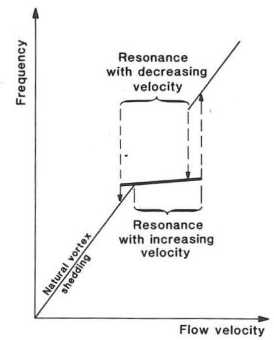


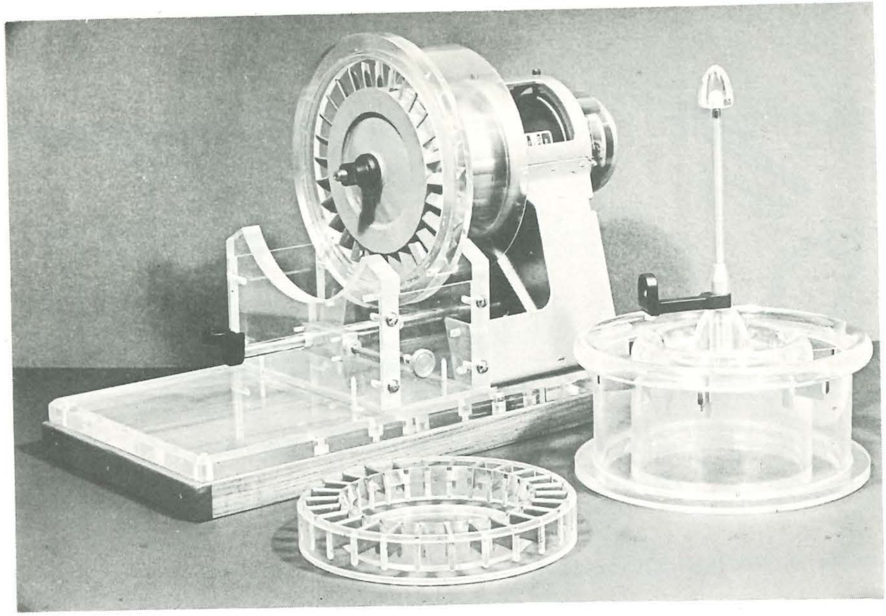
Fig 24 Single plate in wind tunnel



VARIATION OF MEAN VORTEX SHEDDING FREQUENCY WITH VELOCITY

Fig 25

Frequency/Velocity plot for a resonance



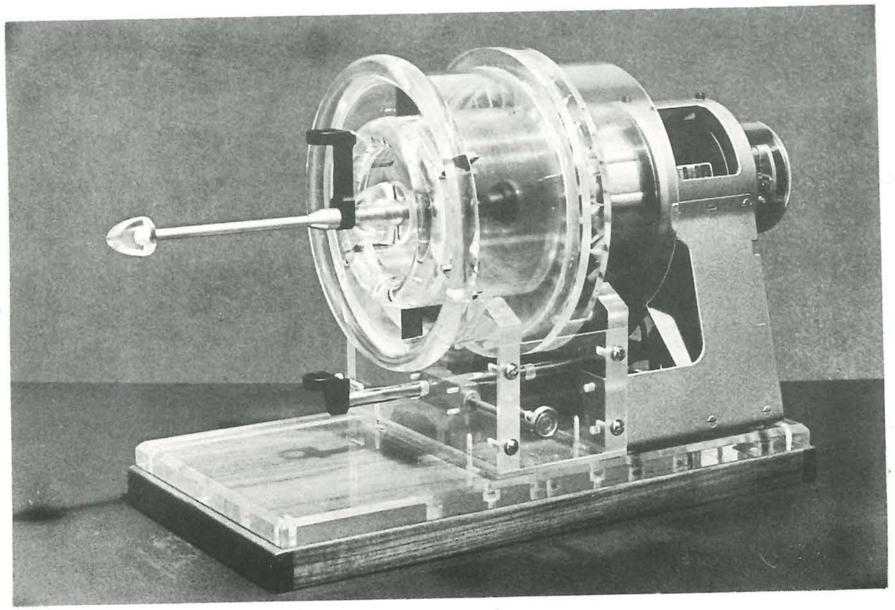


Fig 26

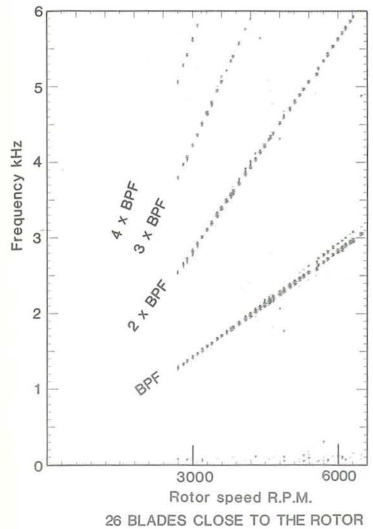


Fig 27 Z plot blade interaction

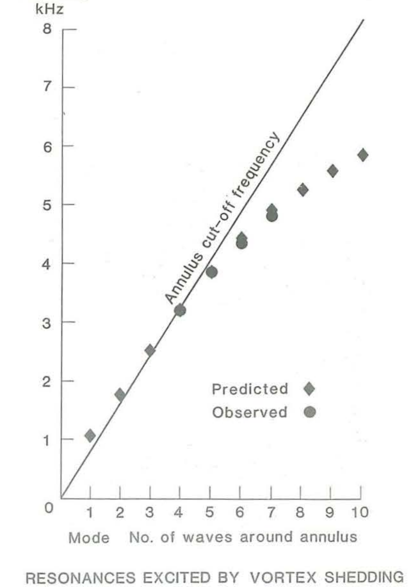


Fig 28 Resonance in compressor rig

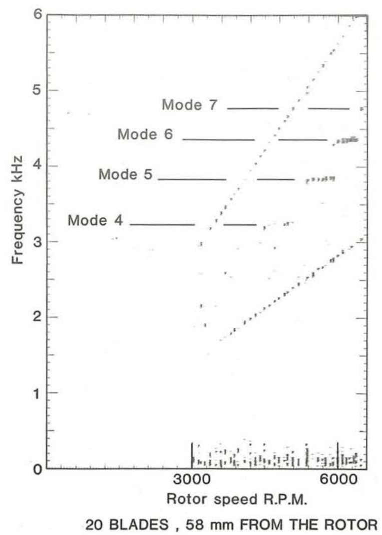


Fig 29 Z plot for resonances in demo rig

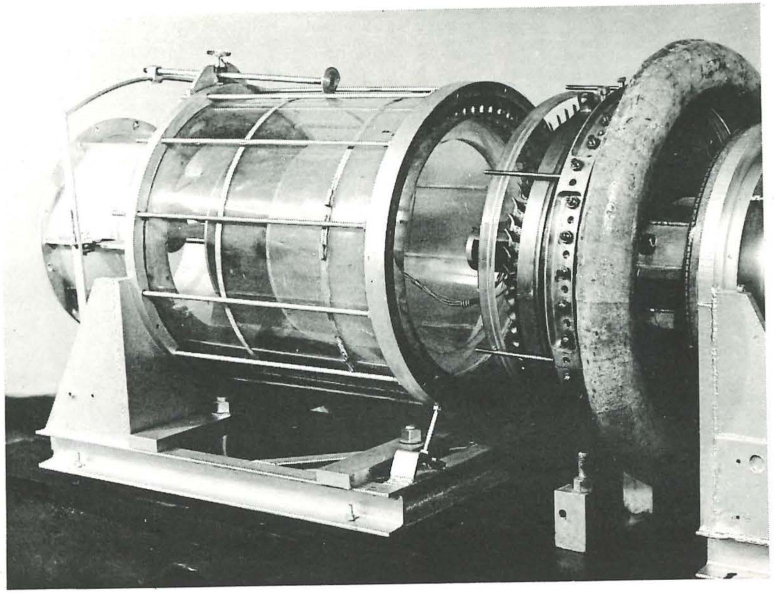


Fig 30 Swansea research rig

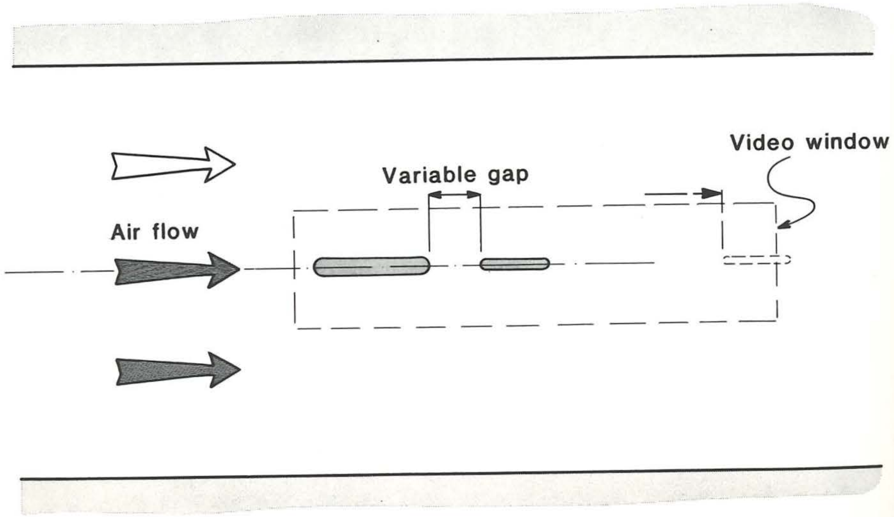


Fig 31 Tandem plates in wind tunnel

As already stated, the circulator design was based on published fan practice because the required pressure ratio was small. The second nuclear power station built by the English Electric Co. was Sizewell "A", with two gas cooled "Magnox" reactors and should not be confused with the recent enquiry concerning a proposed second station on the same site. Two gas circulator designs were considered, one was similar to the Hinkley Point design and the other used technology developed for gas turbine compressors. Fortunately the second was chosen, mainly because the predicted efficiency was higher. As soon as model testing started it was obvious that it was much quieter and the efficiency was indeed considerably higher. When, some time later, the Hinkley Point circulators failed it was a great relief to find that there was no danger of the same problem arising at Sizewell.

7. Vortex shedding

In the course of the Hinkley Point investigation, a small air-flow model was used and this exhibited a further, unexpected, source of single frequency oscillations, vortices shed from spokes supporting the centrebody of the diffuser excited a series of discrete frequencies. It has since been found that this can happen in the blading of any axial-flow compressor and although it was not significant in the Hinkley Point investigation it started a research investigation which has recently become quite important.

The viscous effects in the blade boundary layers generate vorticity which can become concentrated in a series of separate "vortices" which might be imagined to roll along the blade between the main flow and the blade surface. The vortices on each side of a blade have opposite directions of rotation and, when they pass downstream into the wake they combine to form a stream of vortices with alternating directions of rotation. As each vortex is shed the blade is subjected to a force which depends, amongst other things, on the strength and direction of rotation of the vortex. To generate a force on the blade there is a reaction on the gas and shedding vortices with alternating rotation produces a source of both blade vibration and acoustic oscillation, i.e. sound. In the model this effect caused loud, clear, discrete frequency sounds to be emitted, the note changing stepwise as flow velocity was varied. Investigation with a doctors stethoscope showed that each note was associated with a form of resonance comprising a standing wave round the annular space in the diffuser. At that time vortex shedding was not considered to be a potential problem in a turbomachine, it was generally thought of as the source of mechanical vibration and "singing" from telephone wires and other bodies in strong winds were always explained as sound radiated as a consequence of mechanical vibration.

8. Current compressor problem

Over a number of years various aspects of vortex excitation of acoustic resonances have been investigated in the University, not because of a recognised industrial problem but because it was obviously a potential source of excitation which was not generally recognised. In the middle 1970s Rolls-Royce started finding evidence of blade vibration which was consistent with acoustic resonances in the annuli of research compressors. As compressors have been developed to meet the incessant pressures for better performance, vibration associated with acoustic resonances has become progressively more important and a programme of research specifically connected with aero-engine compressors has been under way for the last six years with support provided by Rolls-Royce plc and the SERC.

There are some aspects of vibration with which every one is familiar and these can be developed to assist with understanding the basic properties of acoustic waves in an annulus. One example of "natural vibration" is a simple cantilever of elastic material (wood, steel, plastic, etc.) which will vibrate if the end is deflected and released. It vibrates at its "natural frequency" which depends on the dimensions and the physical properties of the material. If an alternating force is applied to the cantilever the amplitude of vibration will depend on the frequency of the alternations as well as the dimensions and material of the cantilever. This is known as "forced vibration" and the relation between the vibration amplitude and the forcing frequency is of the form shown in Figure 16.

The amplitudes are large when excitation is at or close to the natural frequency, referred to in this context as the "resonant frequency". Vibration at the natural or resonant frequency can also be occur because of a mechanism referred to as "self induced" vibration.

A parent pushing a child on a swing (Fig. 17) is an example of a type of self induced oscillation. If the swing is pulled back and released it will swing at its natural frequency but the amplitude will die down slowly. If the parent pushes the swing when it is moving away the amplitude will increase and the frequency will remain almost unchanged. The energy is provided by the parent but the timing of each push is controlled by his or her reaction to the position and motion of the swing so there is no external frequency control. If the parent pushes when the swing is coming towards them the amplitude will be reduced so the "phase" of the applied force is important. There are many other examples of self induced oscillation in every day life, for example a violin string excited by the bow and the acoustic oscillation in an organ pipe driven by a jet of air.

When compressor or turbine blades are forced to vibrate by blade passing effects the frequency is controlled by the rotation speed and the vibration is forced, resonance due to coincidence with the natural frequency can be disasterous but it can also be predicted and therefore avoided if the blade natural frequencies are known. The forcing effect due to blade passing also "forces" acoustic oscillations in the air in the compressor but there are many frequencies to be considered as the air can vibrate in many different modes. This is true of organ pipes, other wind instruments, violin strings and even the simple cantilever. In the simplest cases successive resonances occur at integer multiples of the lowest or fundamental, i.e. the second resonance is an octave above the first and the next an octave and a fifth, (see Figure 18).

In many cases a fundamental component and various harmonics are present simultaneously, in musical instruments this gives each note its particular quality or tone and few instruments in which the higher components were absent would find places in an orchestra. Provided the amplitudes are small each component can be considered separately and it can be assumed that the consequence of the whole is the sum of the components. In fact this is only an approximation as fluid mechanics is a highly non-linear subject and, at the amplitudes found in turbomachines, so is acoustics. The mathematical tools available at present are not adequate for the complex problems involved so, in most of this work, theoretical analysis is based on small amplitudes and the deficiencies allowed for in subsequent evaluation of the results.

A resonance in an organ pipe with closed ends is shown in Figure 19. At the ends no acoustic velocities are possible but the pressure rises and falls due to the acoustic velocities in the adjoining regions causing air to

move towards and away from the ends. In the centre the pressure gradients cause the air to accelerate resulting in alternating velocities but, at the exact centre, no pressure fluctuations. The maximum velocities occur when the pressure is the same along the whole length of the pipe and the velocity is zero everywhere when the pressures reach their maximum and minimum values at each point. The velocity and pressure fluctuations are therefore "out of phase" as well as having their extrema in different parts of the pipe. This is referred to as a "standing" or "stationary" wave.

Acoustic waves do not only occur as standing waves but can also exist as travelling or "propagating" waves as shown in Figure 20. The waves move continuously away from the source in the same way as surface waves in water, for example as when a stone is dropped into a pond. In this case velocity changes produced by the pressure gradients and the pressure changes produced by the velocities result in maximum pressures coinciding with maximum velocities in the direction of propagation and minimum pressures coinciding with maximum velocities in the reverse direction. As the wave propagates, energy is propagated with it and the wave length is related to the frequency so that the velocity of propagation is the wavelength multiplied by the frequency.

Resonance with a travelling wave is not very common but it occurs in a passage connected in a loop as shown in Figure 21. The positions of extreme acoustic pressure and velocity move round the loop and resonance occurs at frequencies where the length of the loop is a multiple of the wavelength. The fundamental or lowest frequency therefore depends on the size of the loop and the velocity of wave propagation with the higher frequencies increasing as the number of waves increases. The number of waves is generally referred to as the "circumferential mode".

If the loop is an annular passage with a cascade (regular row) of blades or vanes which prevent wave propagation over some part of its length the acoustic amplitude distribution is as shown in Figure 22. The frequency is lower than for a similar annulus with no blades and, either side of the cascade, the amplitudes decrease progressively along the length, the distribution being nearly exponential. In this case, while acoustic energy is propagating continuously round the loop, there is practically no propagation along the length. An annular passage of this sort is therefore effectively closed at the ends as far as acoustic energy is concerned but air can flow through unobstructed.

It is naturally much more complicated in a compressor:

The outer boundaries vary in diameter along the length,

There are blades providing a multitude of surfaces at which the normal components of velocity must be zero relative to the blades and the rotor blades are moving.

The velocity of sound increases in proportion to the square root of the air temperature which rises progressively from inlet to outlet as the air is compressed.

The air is moving with velocities which are not small compared with the velocity of sound along a path which changes direction in every row of blades. The wave propagation velocity is the vector sum of the velocity relative to the air and the local velocity of the air

Even in simple cases acoustic waves do not travel or "propagate" through the air at the "velocity of sound" as they are not plane, uniform waves.

The mathematics of finding small amplitude resonance frequencies for all the possible modes is, in theory, quite manageable given sufficient computer power and programing time but at present there are no precise methods of allowing for the presence of the blades and the air velocities. Furthermore there are no existing programs which calculate all the possible longitudinal modes. This is one of the areas in which some applied mathematics is required.

9. Vortex shedding with and without resonance

The excitation of acoustic resonances by vortex shedding has been investigated in facilities ranging from a rectangular passage with a single plate to a complete compressor stage. The single plate excites a standing wave as shown in Figure 23.

The short video to be shown was made by Dr. S.A.T.Stoneman during a visit to C.S.I.R.O. (Melbourne, Australia) last year and shows vortex shedding from a plate as the flow velocity is varied, the field of view being the area shown in dotted lines in Figure 24. A very persistent "smoke" made by interacting sulphur dioxide and ammonia is introduced upstream. The frequency varies as shown in Figure 25 and the light is flashed at approximately the resonance frequency.

Initially the velocity produces vortex shedding at a frequency well below the acoustic resonance of the space and rather disorganised oscillations are seen downstream of the plate. As the velocity increases the "natural" vortex shedding frequency increases in proportion until it locks on to the resonance and sound is radiated. The vortices are now highly coherent. Further increase in velocity takes place with only a small increase in vortex shedding frequency until the vortices suddenly become less coherent and the mean frequency jumps to the natural shedding frequency well above the resonance. Reducing velocity repeats the sequence in reverse except that the changes take place at slightly different velocities.

The analogy with the child on a swing is that the acoustic velocities correspond to the backwards and forwards motion and the acoustic pressures to the potential energy at the end of each swing. The energy input from vortex shedding then corresponds to the work done by the parent. Large acoustic amplitudes result when each "push" is triggered at the correct time by the acoustic velocities in the same way as the push on the swing is triggered by the parent's observation of the motion of the swing.

10. Demonstration of forced acoustic waves in an annulus

The shedding of vortices from blades in a compressor can excite any of the possible annulus resonances if the shedding is locked to the waves to produce a self induced oscillation. Besides self induced resonances, forced acoustic oscillations occur in the annulus due to blade row interaction and a demonstration of the response will help to clarify the resonance problem.

The small, single stage compressor shown in Figure 26 has been designed and made in the Mechanical Engineering workshop. Ideally the

demonstration should start with no blades other than the rotor, however the inner part of the intake has to be supported and so there are six spokes, they are as thin as possible and are located as far from the rotor as possible.

The maximum axial velocity is approximately 35 m/sec (114 ft/sec or 78 MPH) which is of the order of one tenth the value you might expect to find at full speed in an engine compressor. Ideally this configuration would produce very little noise apart from the effects of air turbulence because there are no fixed blades close to the rotor. In fact some discrete frequencies were produced which can be identified as acoustic modes. It has not been established whether the excitation comes from vortex shedding from the rotor or the intake support spokes but they serve to illustrate how difficult it is to avoid excitation.

A row of flat blades inserted immediately upstream of the rotor produces a blade row interaction effect. One of the earliest analyses relevant to this was made by Tyler and Sofrin in the USA in the early 1950s. They analysed the propagation of a wave in an infinitely long annulus of constant inner and outer diameters. They were interested in excitation due to rotor/stator blade interaction but did not investigate the interaction mechanism, they used the fact that any rotor blade passing any stator blade produces a similar disturbance, the exact nature of which does not affect the problem of transmission to the outside of the machine. The numbers of blades in rotor and stator rows are generally different so if a given rotor is in line with a stator blade at one instant the next blade round comes in line with a stator when the rotor has moved a distance equal to the difference in the circumferential spacings of the rotor and stator rows giving a "vernier" effect. As a result interaction occurs progressively round the annulus, the point of interaction rotating either backwards or forwards at a speed which can be several times faster than the rotor rotation speed. The number of waves or lobes depends on the difference in the numbers of blades. In the demonstration model there are 28 rotor blades and 26 stator blades designed to generate a 2 lobe interaction which rotates at fourteen times the rotor speed. As this is for demonstration purposes the rows are placed as close together as possible to maximise the interaction.

In all cases the frequency of the disturbances is given by the number of blades and the speed, the display shows speed in R.P.M. so the frequency is speed multiplied by 28 and divided by 60, i.e. speed multiplied by 0.4333. The velocity of wave propagation is the number of lobes multiplied by the blade passing frequency and is, therefore proportional to rotor speed. The analysis shows that there is a critical propagation velocity which corresponds to a supersonic wave velocity at the outside wall of the annulus and a subsonic velocity at the inside wall. Below the critical velocity the amplitude of the waves rotating in the annulus decreases exponentially with distance from the source, or, in other words, the sound pressure level in decibels decreases linearly with distance. Further analysis shows that in this condition no acoustic energy is propagated along the annulus so, in an ideal case, the noise generated would not be heard outside. If the propagation velocity is above the critical value the wave fronts are swept back like the shock waves from supersonic aircraft or the surface waves from a boat. In this case energy is propagated along the annulus and so out of the end of the machine to be heard by anyone unfortunate enough to be near.

The calculated critical value for the demonstration occurs at a speed of 3480 RPM. and it is convenient to check the mode while running below this. To show the pattern there are two microphones, one fixed so it can be used as a reference and one on an arm which rotates near the air intake. The two traces on the oscilloscope are swept across by a common time base, the signal from the fixed microphone being used to control the start of each sweep. The display is therefore a graph of pressure against time which is redrawn every few cycles. When the two traces peak at the same time the signals are in phase and, as the arm is rotated, they go out of phase and continue to move until the difference in timing has reached one complete cycle, further rotation gives another cycle and the arm is back where it started, i.e. two cycles for once round the annulus showing that we have a two lobe pattern. The progressive phase change with constant amplitude indicates a travelling wave. The lower instrument shows the spectrum from each microphone and peaks are clear at the blade passing frequency which is twenty-eight times the rotor speed.

As the speed is increased through the "critical" or "cut on" speed. the amplitude of the trace on the oscilloscope increases by a factor of ten showing the predicted increase in transmission. The greater number of waves on the screen corresponds to the increase in frequency and the spectrum analyser also shows the increase in amplitude and frequency. Rotating the microphone still shows that it is a two lobe pattern. As speed is increased further the amplitude falls a little and then rises again but never drops to the levels observed below the critical speed.

Figure 27 presents the results obtained by running the compressor at a series of speeds and recording the signal from a microphone near the air intake. Each sample is analysed to obtain a spectrum and a vertical line drawn with the pen moving sideways in a zig-zag motion with an amplitude proportional to the sound level in decibels. At low levels the pen is raised so the "lines" you see give the relation between frequency and rotor speed of the peaks in the spectrum. The impression of changes in the width or intensity of the lines correspond to the changes in sound pressure level. In this case the lowest line corresponds to the blade passing frequency and the increase in amplitude above 3500 RPM can be seen clearly. The further lines of peaks are at multiples of the blade passing frequency, the interaction process does not produce pure tones but all possible harmonics may be present. In the Hinkley Point circulators the largest component was at twice the blade passing frequency.

The cut off frequency for each mode is important in relation to noise radiation from compressors as designers can select blade numbers to avoid the conditions above cut-off and so minimise the noise.

11. Demonstration of acoustic resonance in an annulus

With blade row interaction the number of lobes (waves) is fixed by the numbers of blades and only one "Mode" has to be considered, there is no such restriction with self induced excitation and any resonance for which there is a source at the resonance frequency will build up in amplitude if the rate of energy loss is less than the input. In a compressor the annulus is not infinitely long and the actual distribution is always somewhat more complicated than for a single cascade in an infinite annulus as shown in Figure 22. The end effects are however very similar with little loss of acoustic energy so the amplitude is controlled by a number of factors including:

i. the circumferential mode and the longitudinal amplitude distribution

ii. losses through the containment walls, which depends on rigidity and damping,

iii. the characteristics of the source, when the system responds at high amplitude the source may be unable to provide further input and a stable amplitude is established, and

iv. the non linear nature of acoustic waves of large amplitude.

The model can be changed to allow this to be demonstrated, the blades close to the rotor are removed to reduce the blade passing effect to low levels and a new intake section with twenty blades well away from the rotor is fitted. The twenty blades comprising the annular cascade have semi-circular trailing edges which are known to give powerful vortex shedding excitation. In the absence of any resonance effects the mean frequency of vortex shedding would increase in proportion to the velocity but the shedding would be somewhat random and there would be no corellation between the vortices from one blade and an other. In the model the annulus provides a resonant enclosure and, if there were no blades and the duct was either infinitely long or closed at each end the circumferential modes would have frequencies equal to the duct "cut-off/cut-on" frequencies shown by the straight line on the graph in Figure 28. Frequencies predicted for the model by a relatively simple numerical solution are as shown for modes zero to ten. Because of the combination of the cascade and the finite length of the annulus the predicted frequencies are above the line for low order modes and drop below the line as mode number increases.

As the model speed is increased a single tone is heard above 4500 rpm and the frequency remains practically constant until there is a jump to another note, if the speed is reduced gain the new note persists for a while and then switches back to the original tone. In this case the lowest possible modes are not excited and, in all, four modes are excited before the motor reaches maximum speed (it is actually being oversped some 30 % compared with the makers rating) but at least three more would be found if the motor speed could be increased sufficiently. The audible tones are modes four, five and six and mode seven has been measured with a microphone. These are the lowest modes for which the predicted frequencies are below the cut-off frequency. Figure 29 shows the measured results and the resonances can be clearly seen at frequencies between the first and second components of the blade passing effects. At each frequency the mode can be checked by rotating the microphone and counting the phase changes as before.

12. The effect of blade row spacing on excitation

The Swansea research compressor rig (Figure 30) is larger than the demonstration but it generates resonances in the same way and many different blade configurations have been tested. One of the most important discoveries so far has been that the axial distance between the blades shedding the vortices and the next row downstream has a marked effect on the excitation of resonances, some spacings producing powerful oscillations while others reduce the amplitudes of all modes to very low levels. At some spacings, increasing speed results in two series of resonances with the same modes and frequencies but excited at different speeds.

13. Tandem flat plate tests

It has been established that the effect of the spacing is due to the vortices shed by the first row interacting with the second row to generate a second source of acoustic energy at the vortex shedding frequency. The phase difference between the two sources depends on the spacing and the net result is to increase the net acoustic energy input at some spacings and reduce it at others. This indicates that one possible method by which acoustic resonances in a compressor may be eliminated is by manipulation of the spacing between blade rows. Complete quantitative understanding of the effect will be required before it can be used with confidence and a large investment of research effort will be directed to this end.The inadequacy of our present understanding was illustrated when the model we have just demonstrated was first assembled. There was considerable consternation when it was first tested with the twenty blade cascade and the resonances were excited at such a low level that they were not audible. As the spacing effect is related to the blade thickness, the thicknesses were varied by wrapping tape round the blades until audible tones were achieved and new blades were made.

To build up a more complete understanding of the vortex interaction effect tests have been performed with a single plate shedding vortices with various bodies downstream. The effect is clearly demonstrated in another short piece of video made by Dr. Stoneman in the Melbourne laboratory of the CSIRO. In this the plates are mounted in a closed passage 244 mm high compared with the plate chord of 67 mm, the video only shows the area around the plate indicated by dotted lines in Figure 31. Initially the light is flashed at a constant frequency close to the resonance and in the second part it is flashed in synchronism with the sound and, when there is no sound there is no light. The acoustic mode is a transverse standing wave with half a wavelength across the tunnel height and the air velocity is constant at about 22 m/second.

14. Conclusion

In my attempt to explain what Mechanical Engineers do I have talked about two fields of activity and the interaction between them. They could both be described as "High Technology". My discussion has been incomplete insofar as I have not mentioned interaction with the multitude of other branches of Engineering which are just as relevant nor have I mentioned the vast range of other Mechanical Engineering activities with which there is no obvious interaction with either power stations or aeroplanes.

Apart from the basic question there were three supplementary questions to be answered:

The first was "why don't more people know what Mechanical Engineers do?"

> The products of Power Station and Aeronautical Engineering affect practically every member of the community. So do domestic appliances, earth moving machines, cars, railway trains and many others machines or systems of machines with which every one is familiar. The existence of such machines is taken for granted and there is generally no reason for any one to think about who designs or makes them, at least until something fails to function correctly. The lack of awareness of Mechanical Engineering is also partly due to the subdivisions of the subject, many of which have titles of their own, for example Aeronautical Engineering and Marine Engineering. The Mechanical Engineering content of these subjects is generally taken for granted within the industry and of no interest outside, even in the cases in which it is the dominant component. To put it simply, Mechanical Engineers are taken for granted.

The second question was whether there is a "connection between the present state of British industry and the apparent lack of appreciation of the contribution made by Mechanical Engineers"

> Comparison with other countries in which Engineers are held in much higher public esteem suggests that there is. They are generally the countries has developed rapidly and taken over our traditional markets for both small mass-produced products and for large items such as power-station plant. For too many years we have undervalued Mechanical Engineers and even now, every entrant to the profession has a target of "management" as the only way to respectability and comfortable living. The Aero-engine industry has a much better record than most in this respect. The product is very complex and, if an unreliable engine was put into airline service, there would be an unacceptable risk to human life. In these circumstances maintenance of the highest possible Engineering standards is an essential ingredient for commercial success.

The third question concerned the advice and even coercion from higher authority to broaden Engineering education and training to encompass ever more diverse subjects.

> For many activities this pressure can be justified, there is no doubt that Engineers should be versed in the managerial and social aspects of their activities. It would however be a disaster if there was no future for the professional Engineer who chose to study the technical aspects of his work in depth, particularly as the frontiers of knowledge are continuously advancing and Engineering is becoming ever more complicated. For my own part I have always chosen the technical in preference to other aspects and have no regrets. I have gained a great deal of personal satisfaction from solving design problems and contributing to the production of reliable machines as well as engaging in the research which is necessary to support other designers.
>
> The problem which does not receive enough attention is that most of the people with whom Engineers interact on the managerial and social side see no advantage in becoming literate in Engineering matters. It is surprising that Universities do not offer any form of "Engineering" as a supplementary course for students intending to graduate in other subjects which may lead to careers in or related to Engineering. Presumably they are not offered because there is no demand.

15. Acknowledgements

I would like to thank the many people who have assisted with the preparation and presentation of this lecture, and I hope they will not mind if I do not name them individually.

I also wish to acknowledge the kindness of the following for supplying illustrations and/or allowing me to reproduce illustrations from their publications:

Brush Electrical Machines Ltd. (formerly Brush Electrical Engineering Ltd.)	Figure 1
The Central Electricity Generating Board	Figure 2
Rolls-Royce plc.	Figure 7
G.E.C.-Ruston Gas Turbines Limited (formerly The English Electric Co. Ltd.) With particular thanks to Dr. W. Rizk for his efforts in finding some of the original photographs.	Figures 11, 12, 13 and 14