FUTURE TRENDS IN PROPULSION

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ABSTRACT

The prediction of future trends in propulsion also requires an examination of past achievements. Continued progress is foreseen. In both civil and military fields, aircraft speed is an important parameter determining the configuration and technology of the engine. In civil designs, increase in bypass ratio will improve fuel consumption, the exact configuration being speed-dependent, but the advance must be achieved in a cost effective way. In military designs, while the configuration may be less likely to change, major improvements in weight and cost will appear. V/STOL aircraft will move from subsonic to supersonic. Hypersonic propulsion will require radical new concepts. Computer assistance will increasingly apply to all phases from design through to production.

INTRODUCTION

In looking forward at the future of aero-engine propulsion, we must also look back, considering which trends may be extrapolated and where there may be step changes to come. The last twenty years have seen much progress and there is little doubt that there is interesting, indeed exciting, potential likely to be realised over the next twenty. We see no sign of a technology plateau.

In both civil and military propulsion we see the prospect of evolving engine concepts, of improving component performance, of new materials. The research, development and manufacture phases will all be greatly assisted by increasingly powerful computing techniques.

All of this is naturally aimed at improving the products for the benefit of the customer, with great emphasis on reducing costs for operator and manufacturer alike.

If we had to nominate one very significant aircraft characteristic which has a wide influence on the conceptual design of many types of aircraft powerplants, speed would be a strong candidate. The paper will use speed as a parameter against which to examine trends. (see Fig. 1)

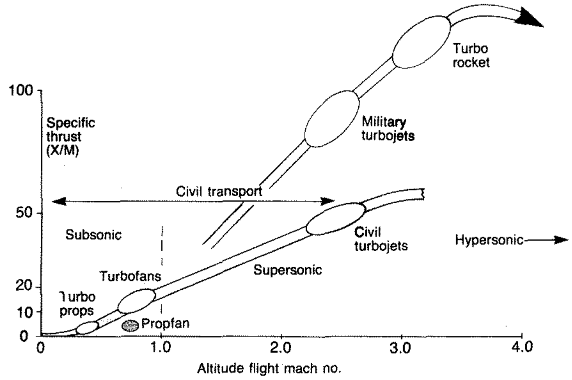

Fig. 1. Air Breathing Engine Characteristics

In the case of civil transport aircraft, speed and size are closely related. Long distance require high speed and hence costly advanced technology airframes and engines carrying large number of passengers to maximise the economic returns.

Short distance travel can afford to use lower speed aircraft, and is less dependent on advanced technology in the airframe and engines, since fuel costs and weight are less significant.

Military aircraft normally place great emphasis on high speed, coupled with high acceleration rates and manoeuvrability. Good range is often a difficult and conflicting requirement. These characteristics dictate low drag, low weight, massive thrust reserves (reheat) and fuel economy.

As we progress further into the higher flight speed regimes of the hypersonic vehicle the concept of the engine becomes even more speed dominated and we see the need for ramjets, duel cycle engines and rockets.

The first section of this paper will discuss the trends we see in civil transport aero engine design, concentrating on the subsonic flight regime. Later sections will discuss

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military and helicopter engines and touch on hypersonic flight. Implementation on these designs in various stages of a product programme will then be reviewed. Of necessity, the illustrations will mainly come from Rolls-Royce experience, but we believe that they will be broadly representative of what is now a world wide industry.

CIVIL TRANSPORT ENGINE DESIGN

It is very much in the interest of the engine manufacturer as well as the aircraft operators to generate designs which embrace the basic principles of low total cost of ownership in the conceptual stage, rather than to achieve it by a lengthy and costly development process.

A cost efficient engine will have among other desirable characteristics, three prime requirements which will differ in order of priority according to the application. They are:

1. High Fuel Efficiency
2. Low Weight
3. Low Price

High reliability and low maintenance cost are always expected, if not always achieved.

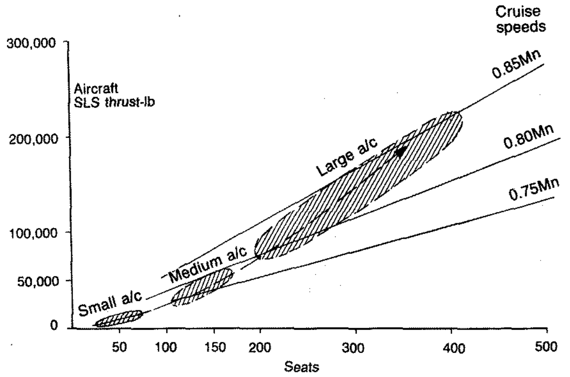

Fig. 2. Aircraft Thrust Requirement Trends

As illustrated on Fig. 2, it is an observable fact that large aircraft tend to fly fast and carry many passengers over long distances. Fig. 2 also shows the very wide range of thrust requirements between the small 50 seat feederliner and the 400 seat long range "Jumbo" type aircraft, a range of 15000lb to around 200,000lb of SLS thrust. The 150 passenger medium sized aircraft requires 40/50000lb of Take-off thrust.

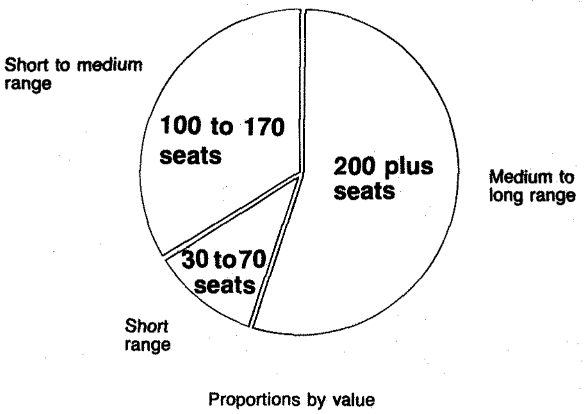

Fig. 3. Powerplant Demand to the Year 2000

Fig. 3 indicates what our sales forecasters believe to be the potential monetary sales value of these three categories of aircraft engines. It will be seen that engines for the larger faster aircraft dominate the scene.

FUEL CONSUMPTION

If we look back to the early 1960's we can observe (Fig. 4) the striking comparison of the Vanguard turboprop and the Caravelle turbojet aircraft in terms of fuel economy or seat MPG, the Caravelle using double the amount of fuel per seat. This was the price we were paying for speed and more comfort in terms of lower noise levels.

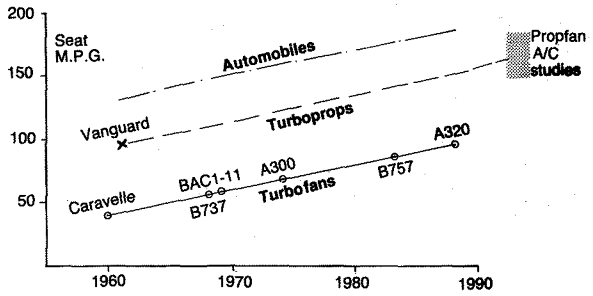

Fig. 4. Fuel Consumption Trends (500 Nm)

It has taken nearly 30 years of very expensive turbofan engine and airframe development to achieve the same standard of fuel economy as the 1960 Vanguard. During those years the turboprop has been neglected, in terms of advanced research until NASA resurrected high speed propeller research in 1975, and produced in conjunction with Hamilton Standard, a propeller which could fly at similar speeds to turbofan aircraft, and with high efficiency. So that we can once again see the advanced turboprop leading in the economy stakes, but it still has a long way to go before it proves its reliability and acceptability as a propulsor for a medium sized civil airliner.

Although there are cases where fuel efficiency is not of prime importance, usually in engines for small low speed aircraft, the current reduction in fuel price has emphasised this situation. Fuel efficiency has what we might call a "snow-ball" effect on Direct Operating Cost in the design stages of the aircraft and engine. A large improvement in fuel burn not only brings an immediate impact in fuel costs but also reduces engine size, weight and cost which in turn may reduce airframe size, weight and cost.

An 8 to 10% improvement in DOC seems to be a reasonable target to aim for when launching an all new aircraft with significant advances in technology. Fig. 5 attempts to show the relative effects of a large change in fuel price on the selling price of the total aircraft to maintain a 10% improvement in DOC. In both cases it has been assumed that the improvement in fuel burn due to the new engine is the same.

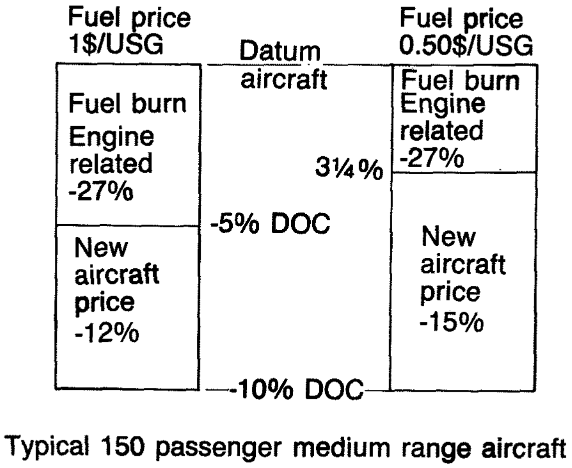

Fig. 5. Influence of Fuel Price

The Datum aircraft is a typical 150 passenger medium range turbofan powered aircraft. The new aircraft is powered by propfan engines and shows a 27% fuel burn improvement. No improvements in airframe aerodynamics, or weight reduction from advanced materials have been included. It will be observed that the target price reduction for the new aircraft is relatively insensitive to fuel price, increasing from 12% to 15% due to a 50% reduction in fuel price.

In reality the airframe will also make a substantial contribution to reducing the fuel burn in addition to the engine, hence reducing the amount that the airframe price has to be reduced. The question to be answered is, will new manufacturing methods be capable of off-setting the cost of higher technology and succeed in achieving the necessary overall price reduction?

TRENDS IN BYPASS RATIO

Referring back to our introductory statement that if we had to define one characteristic of the airframe which would determine the conceptual design of the engine it would be speed. For civil transport, speed, size and range are closely connected. See Fig. 6.

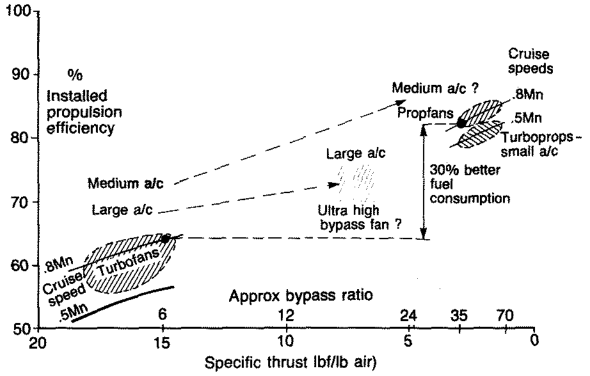

Fig. 6. Bypass Ratio Trends

With the exception of the executive jet aircraft which provides transport for a few, small aircraft tend to be short range, and hence high speed is not very significant in the operating economics. The engine however needs to be cheap to purchase and maintain. The airframer will also follow the same criteria. The conventional turboprop flying at speeds up to about 0.65MN is ideally suited. The very high bypass ratio of the propeller with its very high propulsive efficiency allows the engine designer to produce a simple engine of very modest thermal efficiency and still have a respectable fuel consumption.

The medium range aircraft and the larger long-range aircraft flying at speeds in excess of 0.7MN have currently no other choice than the turbojet or turbofan engine of varying degrees of bypass ratio. Since the introduction of the bypass engine into civil passenger service in 1950, the Rolls-Royce Conway, bypass ratios have progressed from the very modest 0.4 to around 6 for the latest engines. Limitations on bypass ratio have been imposed by the penalties in weight, drag and cost from the increasing size of the installation for a given thrust, with today's standard of technology.

Clearly then there is a great incentive to dispose of the cowling with its weight drag and cost, hence the effort in the US on the unducted fan and propfan engine concepts.

The medium range aircraft of 110 to 170 passenger capacity flying at speeds up to around 0.8MN appears to be a suitable candidate for the open rotor propulsor. Its thrust and range requirement is such that it is a suitable candidate for a twin engine installation, and a rear fuselage pusher configuration is attractive from noise considerations. Speculation now rests on the economic justification of an all new aircraft and untried new powerplant with its attractive fuel consumption but with doubts on community noise, and integrity.

However, disposing of the cowling is not the complete solution to our problems even supposing we resolve the obvious questions.

The faster, very large aircraft cruising at speeds of around 0.85MN or above are operating at a condition where the blading efficiency of the propfan or advanced propeller is starting to decline. It is possible that with further research into blading aerodynamics that this decline can be further delayed, but the real problem lies with the size or number of engines required and their positioning on the aircraft.

The aircraft we are talking about is going to require a take-off thrust of around 200,000lb. It is difficult to visualise twin rear fuselage mounted propfans of 100,000lb thrust each. It also would be quite a problem mounting 4 propfans under or ahead of the wing. Wing performance would be adversely influenced by the high Mach No. propeller slipstream. Other problems of a mechanical nature would be very difficult to resolve, e.g., the development of a 40,000 SHP gearbox and its cooling system or the sting mounting of a contra-turbine-driven pusher engine used as a tractor.

For these reasons attention is being paid to looking hard again at very high bypass ratio cowled engines of unusual configurations to see if new techniques in installation design can push the optimum bypass ratio to a much higher level and reap the potential of improved propulsive efficiency.

TRENDS IN THERMAL EFFICIENCY

As we noted earlier, the three prime characteristics of a cost efficient engine are Fuel Efficiency, Low Weight and Low Price. The priority given to those three characteristics is determined by the aircraft type. See Fig. 7.

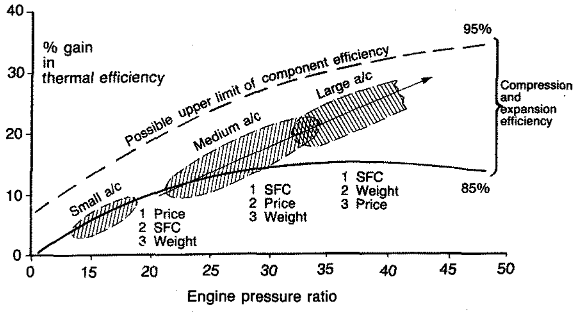

Fig. 7. Trends in Thermodynamic Cycle

The low speed small aircraft places emphasis on engine price, then fuel consumption, followed very closely by weight. It does not pay to design for high thermal efficiency obtained by high cycle pressure ratios and temperatures. The cost of this technology is too high for a small engine. Thus the turboprop engine tends to be of modest pressure ratio 15 to 20, rugged design with few components. The low thermal efficiency being partially compensated by the high propulsive efficiency of the propeller.

The medium range, medium sized aircraft of 110 to 180 passengers needs to fly at speeds in the region of .75 to .80 MN, here the order of priority, tends towards placing fuel efficiency as first priority followed by price and weight. The cycle pressure ratio can be increased with economic advantage, component efficiencies are improved with the larger size of engine and we can afford a good standard of material technology to reduce weight.

The large, long range aircraft flying at cruise speeds well in excess of 0.8MN, needs the highest standards of fuel efficiency, and material technology to compensate for the penalty of carrying massive quantities of fuel over long ranges. The design of the large civil turbofan engine is striving to achieve the highest levels of component efficiency, high cycle pressure ratio and turbine entry temperature.
Fig. 8 illustrates that the major impact of high turbine entry temperature is in reducing the size and weight of the gas generator.

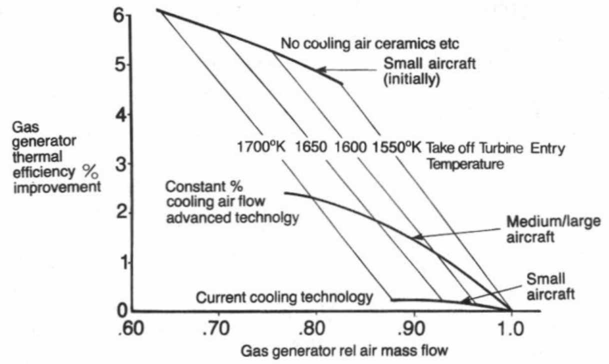

Fig. 8. The Influence of Turbine Entry Temperature and High Temperature Material Technology on Thermal Efficiency

Elimination of cooling air is the key factor in achieving a worthwhile improvement in thermal efficiency, and weight from high operating temperature. It is likely that these advances will first appear in military engines, and very small turboshaft or turboprop engines.

OVERALL POWERPLANT LOSSES

It is interesting to look at the total spectrum of losses incurred by propulsion systems, in order to gain a perspective of the situation. Taking a flight cruise condition of 0.8MN at 30,000 ft, Fig. 9 illustrates that over a very wide range of powerplant types, that is ranging from propfans of bypass ratio equivalent to 70 down to today's more conventional turbofans of 6 bypass ratio, the useful energy available is only of the order of 35 to 45% of the energy provided. This assumes that the thermal efficiency remains unchanged across the spectrum of powerplant designs.

The obvious conclusion to be drawn from this diagram is that we are a long way from achieving the ultimate in fuel efficiency. The two routes open are, firstly a move towards much higher bypass ratios, with all the attendant problems of increased weight, drag and possibly noise. Secondly the achievement of high thermal efficiency, by increasing pressure ratio and component efficiencies, a difficult and costly process.

Alternative solutions employing novel thermodynamic cycles have so far not proved viable for airborne vehicles, but we are confident that the developments in advanced materials, and aerothermodynamics coupled with ingenuity in conceptual design and manufacturing technology will ensure the continuation of the trend towards higher fuel efficiency that we have observed in the past.

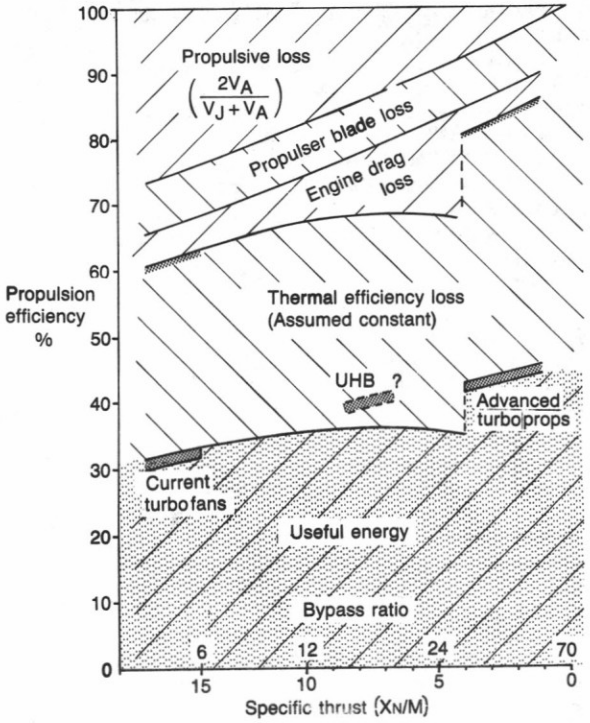

Fig. 9. Powerplant Losses vs Bypass Ratio (0.8 Mn, 35000 ft)

CONTRASTS IN DESIGN EVOLUTION

The following pictures illustrate the change in design concepts of both engines and airframe in our attempts to achieve the highest standards of fuel efficiency and operating economics.

1 RB211 versus RB529

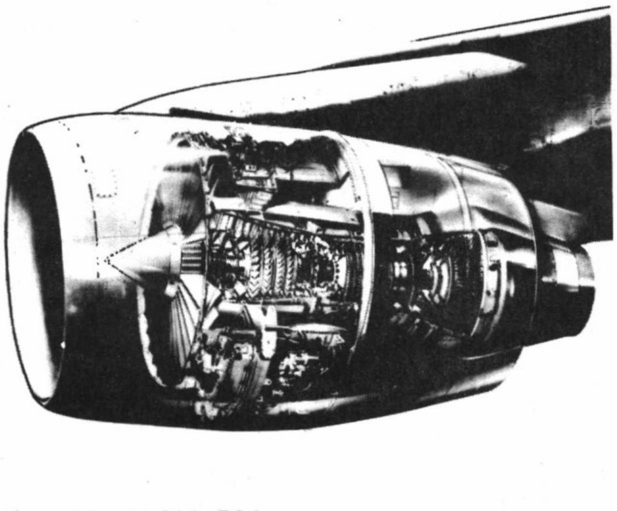

Fig. 10. RB211-524

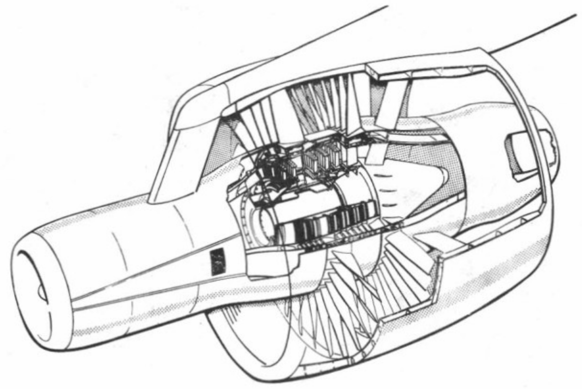

Fig. 11. RB529 Contrafan

2 Tyne versus RB509

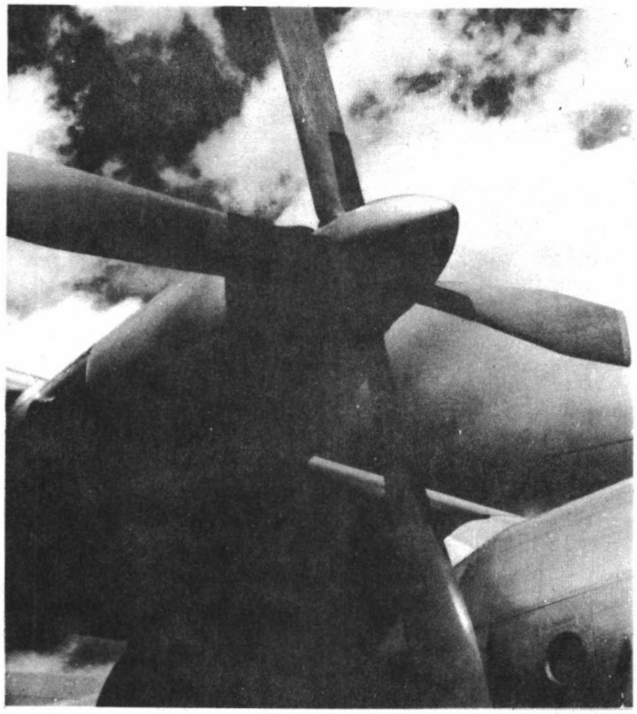

Fig. 12. Tyne Turboprop

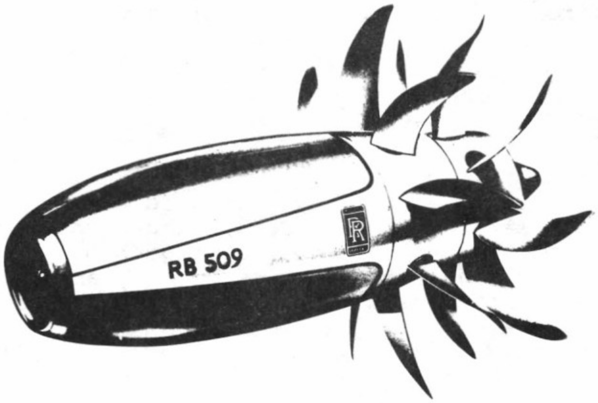

Fig. 13. RB509 Propfan

SUPERSONIC CIVIL TRANSPORT AIRCRAFT

This section of the paper would be incomplete without some reference to the possibilities in supersonic transport. The Concorde fleet is now moving towards completion of its first 10 years in airline service, long enough for the novelty to have worn off. It has become evident, despite the gloomy predictions of the economists, that there is a steady demand for supersonic transport even with premium fares some seven to eight times greater than the lowest economy fares.

The key technology factors which would contribute to the successful Concorde replacement are in very simple terms, the achievement of much higher L/D ratios in supersonic flight, and the successful integration of higher bypass ratio engines without excessive drag penalties. The first requirement has been achieved in wind tunnel experimentation in the US and Europe. Simple higher bypass ratio engines to improve noise levels and reduce fuel consumption are well within our current technology, but if the successful marriage of airframe and engine demands a variable cycle engine, then we are moving into a very costly and lengthy engine R & D programme. Advances in light weight material technology will further enhance the economic viability of a Concorde replacement.

If the hopes of the Concorde enthusiasts are ever to turn into reality a satisfactory solution of the complex, and vast economic undertaking on an international scale must be the first priority.

There are those in the industry who believe that the development of the transatmospheric vehicle travelling at speeds up to Mach 8 could leap frog the more conservative progressive development of a Concorde replacement aircraft.

TRENDS IN CIVIL AND AERO ENGINE CRUISE EFFICIENCY

We have seen in a previous diagram that aircraft seat MPG has progressively improved over the last 30 years after suffering an initial large set-back when the turbojet engine was introduced. If we look (Fig. 14) at the performance of the aero engine in terms of overall efficiency we can observe a very similar pattern.

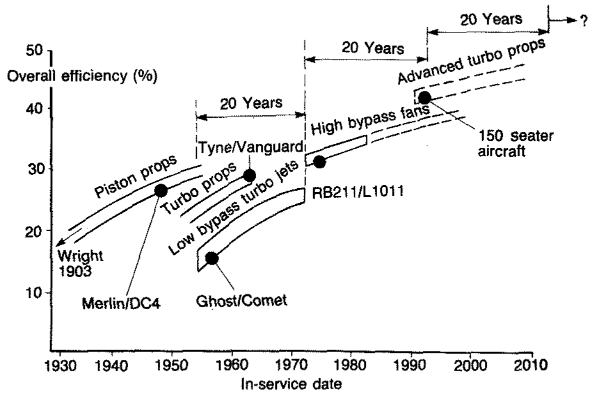

Fig. 14. Civil Aero Engine Trends in Cruise Efficiency

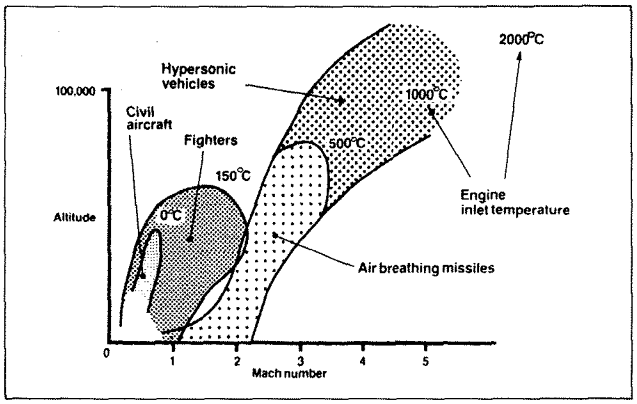

Fig. 15. Flight Regimes for Air Breathing Propulsion

The early piston engined aircraft typified by the Merlin-powered DC4 in 1948 was not equalled in efficiency until the introduction of the complex Tyne turboprop in the early 1960's. This engine is still the largest and most efficient turboprop engine in the Western World. Introduction of the early jet engine in the late 1950's halved the powerplant efficiency, but of course introduced the era of high speed travel. A further period of approximately 20 years elapsed before the introduction of the high bypass ratio turbofan engines restored the fuel economy to the level of the Tyne engine.

Looking ahead we can see that after a further period of 20 years from the early 1970's the possibilities of a further step change in fuel economy by the introduction of engines of very much higher bypass ratio in either cowled or uncowled configurations. A great deal of research and development is still required on these powerplants before they can become a reality.

If history maintains its pattern of progress in our industry then by the end of this century it should become clear what the next big step in powerplant technology is going to be.

MILITARY ENGINE DESIGN

Again it is appropriate to review trends in military propulsion against aircraft speed. Here the range at the moment is very much wider.

Fig. 15 is indicative of the flight regimes for which airbreathing propulsion systems are appropriate and of the technology challenge that is presented if these possibilities are addressed.

Whereas civil aircraft, with the exception of the Concorde supersonic transport, operate with an inlet temperature close to 0°C, present day fighters have to accept inlet temperatures up to 150°C, which begins to place limitations on the use of some low temperature materials.

Ramjet powered missiles flying at three to four times the speed of sound have inlet temperatures up to the 500°C region but so far such systems have not included the use of turbo-machinery. When the potential for hybrid propulsion systems involving gas turbine elements is exploited in the hypersonic speed regimes, inlet temperatures in excess of 1000°C are contemplated, levels more usually associated with the combustion and turbine sections of the conventional engine.

Future trends in technology will perhaps be applied differently in the military field to the civil. In the main area of combat aircraft, no radically new engine layouts are foreseen. Rather, there will be an improvement in the quality of the design - thrust to weight ratios increasing from 10:1 towards 20:1, and turbine entry temperatures moving towards the stoichiometric value, for instance. Our paper must therefore address itself in turn to the different styles of aircraft employed by the military.

Trainer Aircraft

It is perhaps useful to deal quickly with the training activity. In pure propulsion terms, it does not present any particular technology challenges. What has been developed for other military roles can apply. But that does not mean there are no advances in training techniques.

One example is in the new US Navy Undergraduate Jet Flight Training system known as T45TS (Fig. 16).

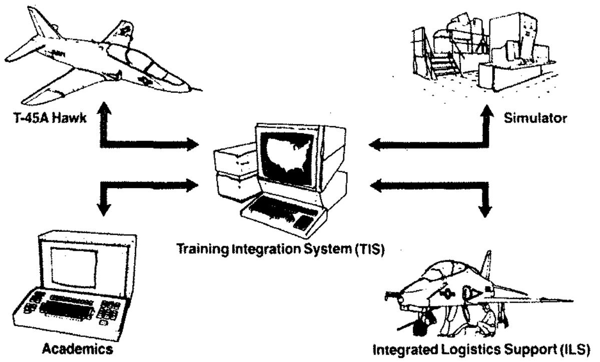

Fig. 16. US Navy T45 Training System

Through the use of computer-aided teaching techniques, advanced flight simulations and a more efficient aircraft in an integrated training programme, T45TS will provide substantial savings - a 42% smaller aircraft fleet and 60% fuel savings compared with the system it will replace when it becomes operational in October 1990. The T45 is powered by a developed version of the Adour engine. If and when a case can be made for a further advance in engine standard for training application, technology will be available to be cascaded from the combat design.

V/STOL Aircraft

In its full scale development and service operation so far, the V/STOL aircraft has been subsonic. Project designs and prototype aircraft from over 20 years ago contemplated supersonic operation and the continued need for flexible deployment of air power over land and sea is sufficient reason for renewed emphasis on both regimes.

The Harrier V/STOL fighter with the Pegasus vectored thrust engine has now been in service for 16 years, and the derivative naval air defence variant, the Sea Harrier, for six years. Together with 14 years in operation with the United States Marine Corps, and experience in the Spanish and Indian Navies, sufficient evidence has been gathered to enable definitive conclusions to be drawn.

In the land-based scenario, supporting ground forces, the RAF deployment of Harriers in Western Germany, has conclusively demonstrated viable and flexible dispersed operation.

In the sea warfare scenario, providing fleet defence and strike capability from small carriers, the Sea Harrier has demonstrated operation in the adverse environment of restricted deck space, severe weather conditions and fast-moving ships. The operation to secure the Falklands Islands confirmed these characteristics in action, and additionally demonstrated a high level of effectiveness in air-to-air combat, deriving from weapon system capability and the inherent target acquisition ability conferred by high manoeuvrability.

Repeated exercises with Western forces (Fig. 17) have demonstrated the combat superiority of the Harrier over contemporary fighters at low and medium altitudes and the self defence capability of the aircraft when operating in the low level strike role.

Venue	Adversary	Kill ratio (Sea Harrier wins: Adversary wins)
Decimomannu 1981	F-15 & F-5E	12:4
Decimomannu 1983	F-16	31:14
Alconbury	F-5E	3:1
NATO Sea Exercise	F-14	3:1 to 10:1
UK	F-4	>10:1
Australia	Mirage III	> 3:1
UK	Lightning	> 2:1

Fig. 17. Sea Harrier Success Record in Peacetime Engagements

Throughout this growing activity, the Pegasus engine has been developed in thrust and reliability to secure its unique contribution to this style of fighting aircraft.

Beyond the current level of 21,000 lb, thrust will continue to grow, accomplished by the traditional methods of increased fan pressure ratio and higher turbine entry temperature. The changes for the next step are illustrated in Fig. 18.

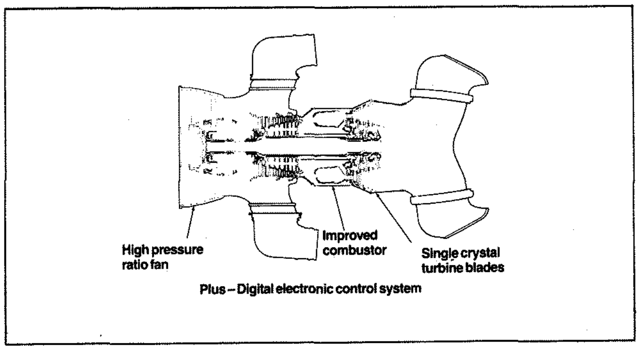

Fig. 18. Advanced Pegasus for Harrier and AV8B

An additional challenge to the design lies in the achievement of these increases within an unchanged, and very short, engine length, necessary to maintain the close relationship between thrust centre and the centre of gravity of the aircraft.

Major further exploitation of the Harrier concept, the challenge of the supersonic V/STOL fighter aircraft continues to be studied. Significant engine testing has been carried out on one arrangement providing thrust boost by the injection of fuel in the fan exhaust - plenum chamber burning. Questions are predominantly associated with the high temperature high velocity jets, essential for supersonic flight, when the machine is in jet- borne flight close to the ground. Potential solutions to these questions have been found, as we shall see later.

While initial emphasis has been on this configuration, others are being studied. (See Fig. 19)

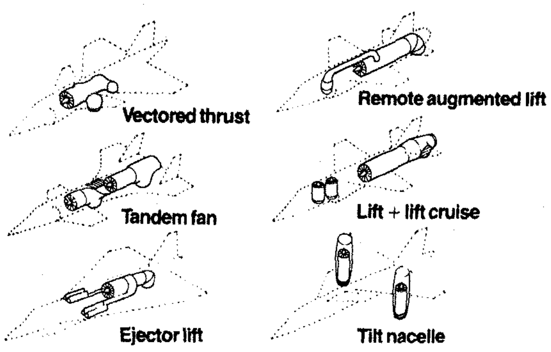

Fig. 19. STOVL Powerplant Options

Two of the study configurations, the ejector lift system and the tandem fan, are conceived to augment the flow of air through the power plant at take-off and landing conditions. The tandem fan is an interesting idea which could find application to other types of V/STOL and conventional aircraft, since the variable geometry features enable it to function as a high by-pass engine at zero and low speed, changing to low or zero by-pass ratio in high speed or supersonic flight.

In a form appropriate to a V/STOL fighter, the tandem fan is provided with front vectoring nozzles to preserve the operating advantages of the Harrier. In the take-off and landing mode, air entering the front fan exhausts through these nozzles, and auxiliary intakes take in air for the main engine compressor. In high speed flight a rotary valve directs the air entering the front fan into the main engine, which then functions as a conventional turbofan or turbojet which can incorporate a reheat system. The air flow in the high speed mode is approximately half that in the take-off and landing configuration.

The potential advantages of this hybrid fan with vectored thrust are:

- Low front jet temperatures at take-off and landing.
- Low fuel consumption at low aircraft speed.
- High thrust per unit of frontal area in high speed flight.

Continued evaluation of these alternatives is expected to lead to some form of demonstration flying in the 1990's. Development of the V/STOL concept to even greater capability is thus assured.

Combat Aircraft

The present-day and future fighter engine presents a range of technology challenges over and above those that have to be accepted for civil engines. It must have supersonic capability with, as has been seen, the attendant high values of inlet temperature and pressure. Reheat is usually a necessity, bringing with it a range of control and handling problems in the presence of high inlet air distortion patterns. The coming generation of unstable fly-by-wire aeroplanes place severe demands upon the engine for power offtake capability to maintain flight control in all circumstances of combat manoeuvre up to extremely high altitudes. At low altitudes, debris ingestion and high speed bird strike set requirements for engine design and factors such as battle damage, infra red and radar signature have to be taken into account.

The flight envelope is illustrated in Fig. 20.

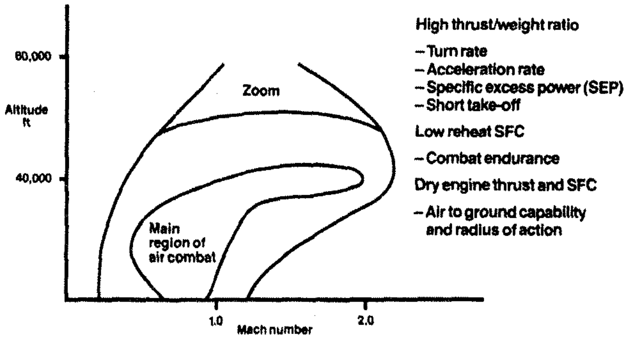

Fig. 20. Advanced Fighter Engine Requirements

The engine requirements, in performance terms, are clear. Continuing and significant advances in thrust/weight ratio, coupled with good combat fuel consumption, are primary objectives. Quantified objectives for cost of ownership and reliability are important additional aspects of the specification.

The progression of military engine technology is illustrated by a comparison of engines past and future, all drawn to a scale which provides the same thrust (Fig. 21.)

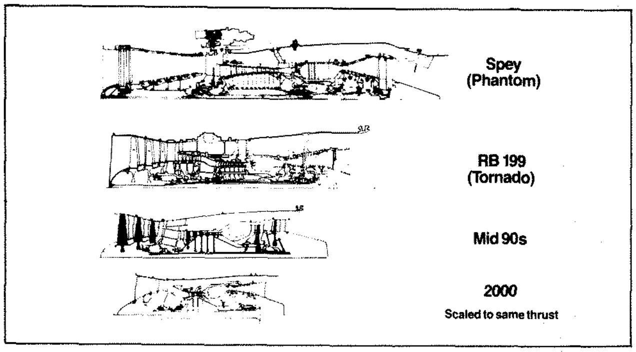

Fig. 21. Advances in Military Engines

The engine arrangement for the mid-1990's has a smaller number of compressor and turbine stages compared with present day engines in service, to minimise the number of parts and hence manufacturing cost. While the main emphasis is on an engine that will confer high levels of combat agility, the strike role must also be taken into account, demanding a degree of multi-role capability and a requirement for low fuel consumption in subsonic flight without reheat.

Further advances beyond the mid-1990's standard, now the subject of intensive development, are being addressed in a far- reaching component programme, which is aimed at providing the relevant technology base for engines beyond the end of the century.

Further increases in turbine temperature will follow from the development of ceramics, although a great deal of experimental proof will be required before adequately reliable components are available. Composite materials will be increasingly used in internal engine structures and the performance compromises will be eased by the introduction of variable geometry.

A design consideration of increasing importance is that of detectability, or stealth. The topic is a wide one covering radar, infra-red and optical signature reduction of fixed-wing aircraft, helicopters, missiles and weapons. It goes well beyond the propulsion system alone. The engine manufacturer is mostly concerned with participating in the design of low RCS intakes and has a major design responsibility for the engine exhaust system and its installation where our main interests are the study of low-signature nozzle configurations, smoke reduction, infra-red suppression and materials development. The trend towards high specific thrust engines for advanced combat and V/STOVL aircraft, exacerbates the infra-red problem, as metal and jet plume temperatures increase.

It may be that, in the military sphere, emphasis on further component efficiency improvements will eventually reduce, unlike the civil. The cost effectiveness of greater complexity and difficult development will not be justified, when compared to work on materials and structures giving reductions in weight and volume, producing thereby the most effective fighting machine.

HYPERSONIC PROPULSION

More economic launching of space vehicles, and the military potential of trans-atmospheric vehicles, are important considerations that have resulted in an intensification of work in air breathing propulsion as a supplement to, or substitution for, rocket motors.

During the 1960's intensive studies were carried out into the engineering design of alternative air breathing engines, partly for missile application but also for long-range cruise aircraft at speeds up to Mach 5 and for recoverable space launch first stages (See Fig. 22).

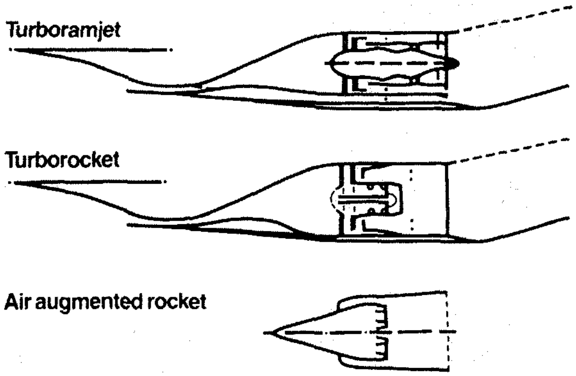

Fig. 22. Hypersonic Propulsion Systems

This work contributed to the successful development of ramjets for ground-to-air missile propulsion up to Mach 3, and the technology acquired assisted in the refinement of the Concorde power plant - Concorde operation at Mach 2 represents the bulk of world experience on sustained supersonic propulsion.

Engines now under study include variants on the turbo-ramjet theme, which can be considered as extensions of the reheated turbofan. The turbo-scramjet uses supersonic combustion to limit the high internal pressures in the engine cycle. The other category of engines is based on rocket fuel combustion, used to drive augmentor fans as in the turbo rocket, or in conjunction with an ejector to achieve the same objective of entraining atmospheric air.

A very considerable advantage in specific impulse is offered by the turbo-ramjet, due to the higher propulsive efficiency compared with the rocket, obtained by the effective reduction in jet velocity using entrained atmospheric air. Fig. 23 shows the estimated weight of fuel or propellant used in reaching orbital velocity, for a conventional three-stage rocket system and for a system in which the first rocket stage is replaced by an air breathing stage using a turbo-ramjet.

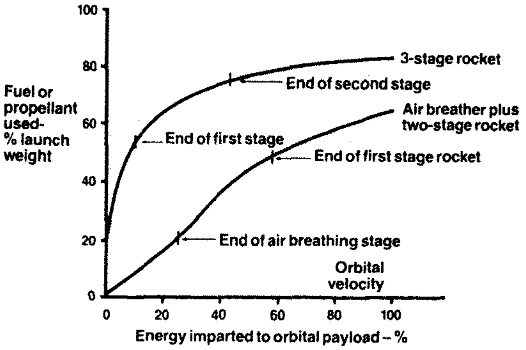

Fig. 23. Comparison of Propellant/Fuel Used

This is, however, not the whole story, and the weight of the propulsion system must be taken into account.

A number of engineering issues arise. Intake and exhaust ducting at the extremely high expansion ratios involved dominates the total power plant weight, and the basic thermodynamic machinery accounts for only 25 to 35%. Integration of airframe and engine can help to minimise the size and weight of intakes, and is essential for an efficient total system.

For minimum fuel burn in acceleration it is necessary to achieve high Mach Number at relatively low altitude, leading to high boiler pressures and challenging structural problems.

It may be concluded that the turbo-ramjet system is probably best for sustained cruising flight in the upper atmosphere at speeds up to say Mach 5.

The field for space launchers is, however, wide open, with a variety of composite power plants involving air breathing propulsion meriting further detailed attention.

The use of liquid hydrogen opens up the field for novel use of turbomachinery with a range of possible concepts that process atmospheric oxygen for combustion in a rocket chamber. Dual cycle power plants enable the advantages of air breathing to be achieved without the necessity for two completely separate sets of propulsion machinery for atmospheric and space flight.

The Hotol vehicle, with a still classified propulsion system, provides a focus for some of this study and experimental work.

HELICOPTER ENGINES

Historically, the speeds of conventional helicopters have risen by approximately 12 knots per decade. Current cruise speeds in normal operational use are around 140-160 knots.

Although speeds of 180 knots are possible with conventional helicopters these are not used in practice, particularly in the civil field, for reasons of acceptable vibration, general fatigue life and payload economics. In military use speeds of 170 to 180 knots may be flown for short periods where a higher degree of vibration can be tolerated.

To overcome this inherent speed restriction the alternatives of the Tilt-rotor, the Advancing Blade Concepts and the Compound Helicopter are being actively studied in both Europe and America. The X-wing is an example of the Compound Helicopter where the tilt rotor is stopped in high speed flight.

In the case of the Tilt-rotor, vibration and drag are reduced by virtue of not having the assymetries of the edge-wise helicopter rotor flow and the rotor tower frontal area. In exchange the wing-tip-mounted engines have a high degree of complexity having to be pivoted and be cross-shafted. Mission specifications call for about 250 knots normal cruise with maximum excursions to around 300 knots for short periods.

The Advanced Compound Helicopter is aimed at a normal cruise speed of about 200 knots rising to 220 knots for high speed cruise with dash capability to 250 knots. In this case the rotor is unloaded and can be slowed while the machine is largely supported by wing lift. This enables the flight envelope to be extended both in speed and altitude while retaining the well-established characteristics of the conventional helicopter.

Conventional Helicopter Developments

In the smaller engine sizes, economical application of technology regularly leads to the creation of families of engines round cores which are largely common. This approach will continue, and is exemplified by the RTM322 family. (Fig. 24)

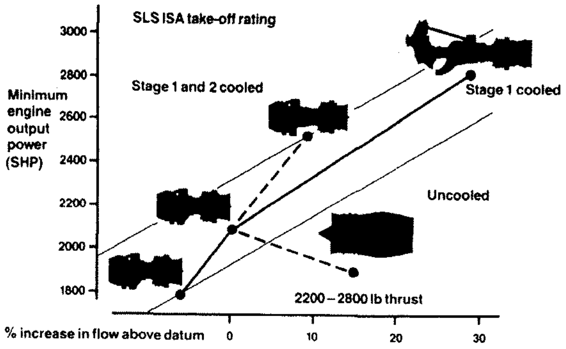

Fig. 24. RTM322 Family

This family of engines spans the power range 1800 shp to 3000 shp, in turboshaft and turboprop configurations. It also includes turbofan derivatives in the 2750 lb thrust class applicable to small business jets and long range missiles and drones.

The general arrangement is typical of many engines in this size range. The engine has a three stage axial compressor with integral blades and discs, followed by a centrifugal compressor giving an overall pressure ratio of 15:1. The reverse flow combustion chamber is followed by a two stage turbine driving the compressor, and a two stage free power turbine driving through a forward mounted gearbox.

The employment of present day aerodynamic design technology has enabled a reduction in the total number of parts to be reduced by 30% compared with existing engines.

Because of the production cost benefits, it is to be expected that the axial-centrifugal compressor arrangement will find itself being used in engines in higher power classes. Increases in engine pressure ratio will be paced by material capability in the centrifugal rotor at the resulting higher metal temperatures.

IMPLEMENTATION

Introduction

So far, this paper has considered trends in engine design in isolation from the programmes which will bring these designs to fruition. It is appropriate to consider the phases of activity which put a timescale to the trend.

Faced with a continually expanding technology base and an increasingly complex and interwoven business scene, the engine company has to contrive a product strategy that covers his chosen market areas in the most cost effective and competitive way.

This will involve a mix of programmes - those built up from a succession of derivative designs, with the less frequent introduction of completely new engine types. Derivatives can, of course, cover a range of applications, for example, as we have already seen, the use of a common gas generator for turbo-prop and turbo-fan engines.

Examination of the various product strategies within the engine industry illustrates different philosophies at different time periods, depending on circumstances, particularly financial, but also collaborative.

Cost-effectiveness in either case is ensured by the establishment of an adequate technology base from comprehensive component and demonstrator engine programmes. The certification and production launch phases can then be embarked upon at a low level of risk.

Of particular importance is the continually increasing closeness between the design of a component and the manufacturing processes which it will require in production, driven by continued pressure on costs and competitiveness.

The preceding design sections have illustrated the wide range of requirements and some potential developments in materials, aerodynamics, heat transfer, structures, etc. It is not our intention to cover the whole range of technology acquisition in detail but rather to consider each phase of activity in turn and to make specific illustrations of a number of the more interesting developments.

Research

Perhaps the most fundamental technology which we require is that of the materials in which we work.

The trend towards composites has become very well developed in engine nacelles and is now entering the structures in cooler areas of the engine. In the higher temperature end, ceramics and high temperature composites are being examined.

In the choice of materials for discs, requirements for integrity, weight and cost must all be taken into account.

An illustration is titanium which has been developed to cover the whole compressor rotor system of the highest current pressure ratio cycle in a commercial engine (See Fig. 25). Further developments towards 1000°C are under consideration.

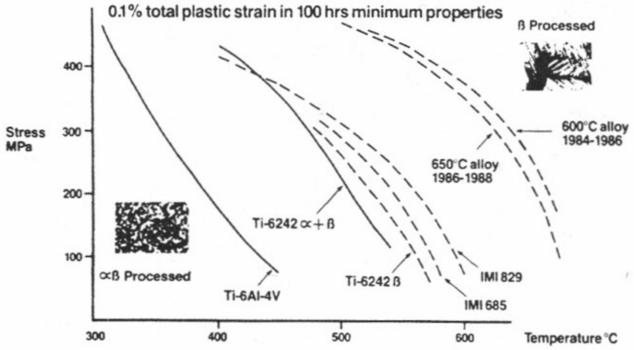

Fig. 25. Creep Strain Properties for Various Titanium Alloys

Until the last few years, designers had to content themselves with theoretical techniques of a very simple nature and depend upon successive refinement using tests and correlations of test results to make progress. This was very costly in staff and equipment and was time wasting.

Now, increasingly, in the field of design and process definition of new materials, this empirical approach is being replaced by a much more thorough and integrated approach, following in the materials field the lead given in the application of aerodynamic theory.

Manufacturing process modelling is concerned with understanding, with great thoroughness, what takes place during the manufacturing cycle. It is important because it addresses all the factors which govern yield, a dominant factor in unit cost, the ability of the part to perform the required design duty and the consistency with which this can be done economically.

The modelling may concern understanding the way molten metal freezes in a mould to form a specified intricately shaped part. In other examples, it will concern what takes place in the metal as it is forged to the right shape, giving the right material grain flow and internal microstructure.

There are many other examples that can be given. Computational fluid mechanics has made great progress. It depends upon powerful computers, sound theories and perceptive accurate instrumentation measuring at the physical phenomena level.

Turning for instance to blading research, one of the best examples is in fan design. Fig. 26 shows the use of laser holography to give flow visualisation in a running fan, while laser anemometry reveals the air velocities in magnitude and direction to enable a direct comparison to be made in every detail with the computerised theoretical model of the flow.

Holography and Anemometry techniques are used to visualise the shock structure and velocity contours within the blade passage

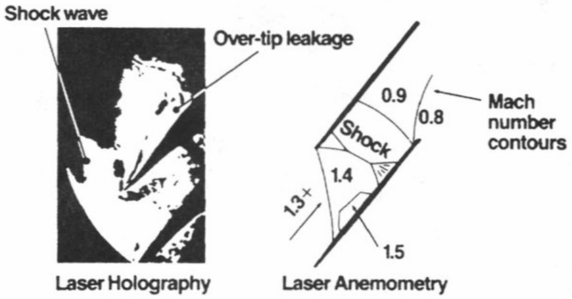

Fig. 26. Flow Visualisation - Rotating Fans

If an exact match is achieved, we know we have fully understood the aerodynamic design at the fundamental physical phenomena level of detail. If there are exceptions to this, then we can see just what is wrong and what is exactly right. In this way we can concentrate on the important items and make rapid progress scientifically and hence with great precision.

Increasingly, these techniques are applied to the multi-stage compressors and turbines. Correspondingly, the measurement and design tools are being moved forwards from the point where only a world class expert can use them to the more widespread use by ordinary mortals.

The computerised method used to design a component can be further used to define the condition and precise mode of failure that the worst product of the production process will fail at, with the necessary margins. This enables us to specify an efficient confirmatory test programme eliminating the need for exploratory tests, diagnostic tests and excessive test failures.

Even very complex occurrences, like bird impact damage on the fan, can be modelled, leading to efficient, confident and explainable confirmatory testing (See Fig. 27).

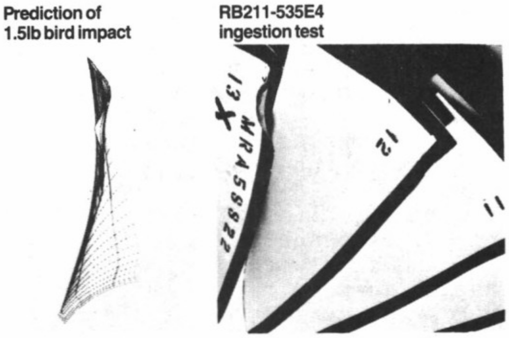

Fig. 27. Finite Element Impact Analysis

A wasted, non-confirmatory test is costly, time consuming and, worse still, often contributes inadequately to the understanding.

In many of these fields, we now see the promise of an ideal sequence and flow of data and control, totally based on the use of the computer, from the analysis of research testing, through the definition of the design, incorporating the confirmation of the performance of that design and finally into the production stage by means of numerically controlled machine tools.

Demonstration and Development

The use of demonstrator engine work to minimise risk at the start of a development programme has been widespread for many years. Let us review just one recent example.

The technologies associated with advanced V/STOL have been extensively studied in model tests and it has been found necessary to extend this work to full scale testing to establish confidence in the interpretation, concentrating so far on the plenum chamber configuration already described.

The equipment consists of an airframe including an installed power plant, mounted from a gantry so that engine tests can be carried out in the region of ground proximity effects with jets directed downwards. Rate of ascent and descent can be controlled, together with pitch and roll angle. The rig is equipped with full instrumentation to investigate flow conditions in the intake and round the airframe (See Fig. 28).

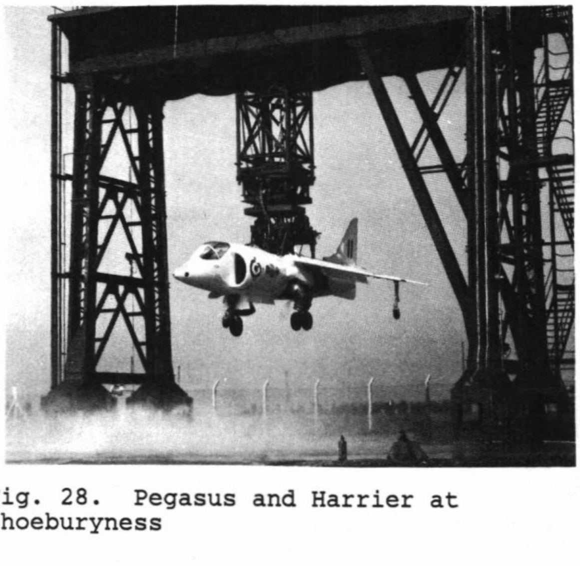

Fig. 28. Pegasus and Harrier at Shoeburyness

Testing has been carried out using this rig on a modified Pegasus engine. While this provides the necessary thrust boost, it substantially increases the temperature of the jets. Optimisation of the nozzle geometry, providing control over the up-draught of hot gas, and the design of simple baffles and flow diverters, has established the feasibility of the boosted vectored thrust engine for Vertical Take off and Landing and shows the virtual elimination of the hot gas reingestion problem.

Progress in reducing timescales is another benefit from the more rigorous application of new technologies. Timescale and costs are interdependent to a considerable degree.

A good example is provided by comparison of a number of turbine blade programmes, as revealed in Fig. 29 which compares the style of the Design-make-develop activity. The early programmes were sequential, whereas later programmes are increasingly interactive and overlapping during the design phase.

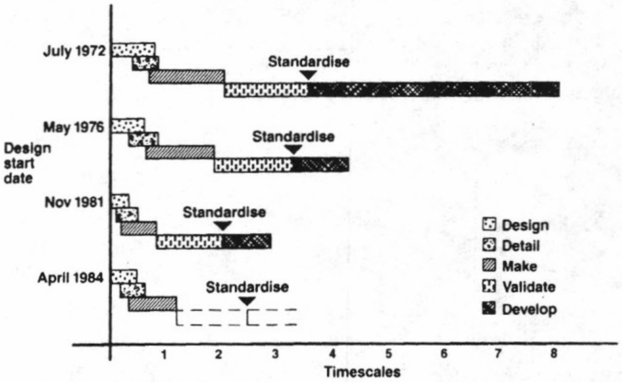

Fig. 29. History of Rolls-Royce HP Turbine Blade Design/Detail/ Manufacture/Design Validation

The corresponding effect on cost is quite dramatic. As is well-known, the cost to develop is much greater than the cost to design. The extra thoroughness of Design without a cost increase has been achieved through the use of computer-aided tools, while the resultant development costs have been much reduced. To a particular and consistent definition, we have been able to measure and plot the trend in the ratio of Development Cost/Design Cost for a number of high pressure turbine blades as shown in Fig 30.

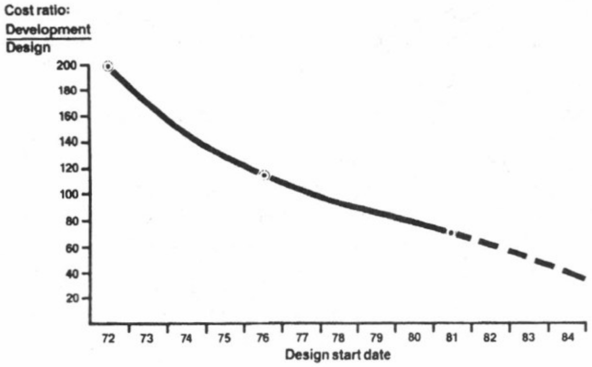

Fig. 30. Progress and Development Cost Reduction through HP Turbine Design Advancement

For a design started in 1972, the development cost was 200 times the design cost. Our latest design in service has been achieved for a ratio of 70, while the latest blade looks like showing an even more promising and affordable ratio of 40.

This striking example is of course largely looking into past achievement, rather than future trend. The rate of fore-shortening and cost reduction may not be sustained in the future in further turbine blade design, but there will be corresponding improvements in other engine components.

Manufacture

Advances continue to be made in both metal forming and in the handling of components. Both involve close integration with the designer.

The challenge that faces Manufacturing Engineering is quite simply this: more and more to translate design intent into a saleable product, to understand and model the process capability, to ensure that the design matches the process capability, to produce with fewer people, to attack that 80% to 90% of the cost which is determined when the designer puts pencil to paper at the design stage and to provide a means of bringing new products and improved performance to the customer in the shortest time, with the minimum risk and the lowest launch and product costs.

An example of metal forming with much potential for the future is the application of electro-chemical machining to the complex shape of a compressor blade. (See Fig. 31)

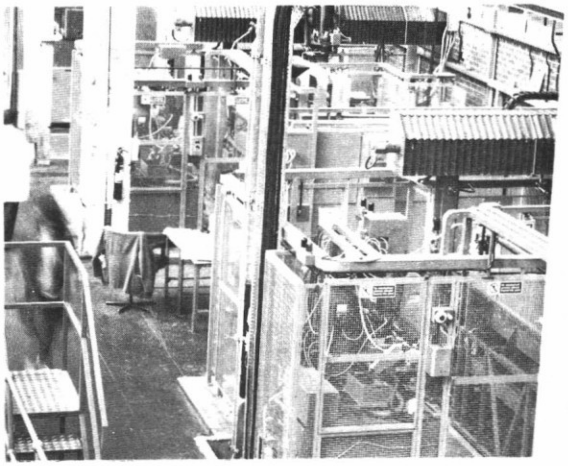

Fig. 31. 360° Electro-chemical Machining Cell

This process means that thin, accurately-profiled blades can be produced much faster - and at lower cost - than by conventional methods. It works on the principle of electrolysis, with the workpiece being the anode and the tool the cathode; the tool surface a near-mirror image of the blade aerofoil surface. By integrating this process into an automated line, finished blades can be produced from bar material - titanium and nickel alloys - every four minutes. In component handling, traditionally, aero engine manufacturers have produced parts in batches. This method minimises total setting and re-setting time but leads to long lead-times and high inventory. The long lead-times mean that this method of manufacturing is slow to respond to change, and high inventory means a poor return on working capital.

The alternative and more recent method - 'batch-of-one' manufacture - has many advantages: it produces short lead-times, which allows a quicker response to change. It entails low inventory and therefore lower costs.

The computer helps with the greater complexities involved in small batch manufacture and it can contribute to the vital element of batch of one - minimum setting time - as each 'batch-of-one' requires the machine to be automatically set for it.

CONCLUDING OVERVIEW

Over the last quarter of a century, the combined efforts of the airframe designer and engine designer have doubled the seat miles per gallon of the civil turbofan propelled aircraft. There are prospects in sight for a further 50% improvement before the end of this century. The current fall in fuel price is emphasising the importance of designing both airframe and engines for low first cost. The development of engines based on common cores will make a major contribution to achieving this objective.

We see similar trends in the technology of the military engine and civil engines, but applied differently. No radically new engine layouts are foreseen in the main area of conventional military combat aircraft engines, but the technology advances will concentrate on improving the thrust to weight ratio and size.

In the military V/STOL field, the Pegasus/Harrier concept will continue to be developed employing plenum chamber burning to achieve thrust boost in the fan exhausts. Novel engine configurations such as the tandem fan concept could offer attractive solutions for supersonic V/STOL aircraft. In the field of hypersonic propulsion there is a return of interest again to the possibilities of using air breathing propulsion to complement, or even substitute for, rocket motors to propel space and trans-atmospheric vehicles.

Power demands of the helicopter are still relatively low to enable the most effective use of the potential efficiency of the gas turbine and in these small power classes will lead to the creation of families of engines based on a small simple core of modest pressure ratio, employing a combination of axial and centrifugal compressor technology.

In the area of manufacturing technology, it will be vital for the conceptual designer, materials and process technologists to integrate their skills at the design stage to ensure that the customer receives new products with improved performance in the shortest time, with the minimum risk and lowest launch and product costs.

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