suggested that commercially pure metal be confined to 130 and 160. Mr. King (English Electric) supported these views, saying that the airframe industry was unanimously in favour of sheet with a 371 specification suitable for cold working.

Mr. Barker (Firth Brown) regarded proof stress and elongation as the important parameters; on austenitic steel a low value of proof/ultimate strengths could be accompanied by poor elongation and better ductility by a high value of proof/ultimate. He inquired whether there was known to be a correlation of this nature. Dr. Inglis thought not; if a greater ratio of proof to ultimate was wanted, it would be provided at the expense of ultimate strength—but the material would never work like aluminium. Mr. Hall (Rolls-Royce) pointed out that sheet to 317 or 318A could readily be used from drum-shaped objects, but parts that needed to be pressed were more difficult. For engine manufacture there was a need for a precipitation hardening alloy which would be aged after fabrication. Where compressor discs and similar components were concerned, an alloy that did not demand a drastic quench was wanted: the material was costly, the utilisation down to 10 per cent, and distortion must be minimised—the ability to cool in air would be welcomed. He added that his firm had used titanium compressor blades without a failure for three or four years.

Applications

Mr. R. L. Preece analysed 1956 sales as follows:—(1) 40 per cent rod for compressor blades; (2) 20 per cent sheet for firewalls; (3) 20 per cent sheet for exhaust and jet pipe shrouds; (4) 5 per cent billet for discs and spacers; (5) 5 per cent bar for small forgings.

In the first category, limitations to more extensive use were of temperature rather than strength; it was desired to use the same stresses at higher temperatures. However, the manufacturers might try developing methods to use tougher alloys than the 40 to 55-ton materials at present in use.

For firewalls it appeared that wider, thinner sheet to substitute for stainless steel was wanted; for the shrouds formability was called for, and commercially pure materials were adequately strong.

Titanium alloy discs and spacers demanded creep resistance and heat-treatments for 371 suitable for thin sections were being sought; assembly by welding might avoid the difficulty of forging to thin sections.

The use of tubes was awaiting enhanced fatigue resistance. Problems associated with galling were holding back some uses, but various surface treatments such as oxidation, anodising, possibly cyaniding, electro-plating or chemical deposition might help overcome them.

Dr. H. W. Shaw examined the value of weight saving in a commercial aircraft. Considering only the increase in payload possible over ranges beyond that to which the maximum payload could be carried, he estimated 1 lb of weight to be worth a yearly profit of from £17 to £22 on short sectors to £70 to £80 on extremely difficult routes. The cost of saving weight by means of titanium was not yet established, but in batch production it might be £20 per pound. Where stressed components were concerned, fatigue life in service might override economic considerations, and because of the cost of the material welded components might be expected to emerge.

Mr. Boorman (Short and Harland) favoured a reduction in the number of specifications, and disliked the present system, whereby suffixes could be called on to differentiate quite different materials.* While titanium was a favoured material for supersonic aircraft, a wing spar box for a subsonic design had shown a weight saving of 14 per cent in titanium. However, torsional rigidity was down—was a higher Young's modulus attainable? He shared the view that hot forming was insupportable.

Mr. R. L. Lickley (Fairey Aviation) observed that his firm made little or no use of titanium, largely because the specifications could not be guaranteed and the consistency was not close enough. Two commercially pure grades and an alloy of 60 to 65 tons, with a proof strength not more than 80 per cent of this, would be satisfactory.

Mr. Smyth (Aviation Traders) said that a high value of proof/ultimate strength was associated with bad fatigue life in aluminium. A badly fitting rivet allowing fretting corrosion to take place had been known to reduce the life of a specimen by a factor of eight; was titanium subject to fretting corrosion? Whether aircraft were designed on safe life or fail-safe principles, long fatigue lives for components were essential if the operator was to show a profit, and the question was whether titanium would excel aluminium in this respect. Dr. Inglis knew of no relationship between fatigue and the proof/ultimate ratio; there was none for titanium. The high corrosion resistance of titanium did not render it immune from fretting corrosion, and cases of the latter had occurred, but no tests had been done. Treatment with an anti-galling compound might be beneficial in practice.

Major P. L. Teed (Vickers-Armstrongs) asked for comments on the confused and contradictory literature concerning the effect of hydrogen. Since stress concentrations were inevitable, he considered fatigue results on smooth test pieces meaningless. Fretting was the first stage in stress corrosion, and he considered the liability of titanium to fretting critical. Dr. Inglis pointed out that hydrogen contents were now well below the levels at which adverse effects had been observed (see above, "Research and Development") being 100 to 130 parts per million. He did not consider fretting corrosion to have been established as a mechanism of failure; it was possible that the galling or tearing to which titanium was susceptible accelerated fatigue.

Mr. Clarke (De Havilland Engine), said that the creep performance of titanium alloys was dubious, because the stability of the material at high temperatures was not established. Because it might result in a material unstable at 400 deg. Cent., he did not favour quenching 371. Dr. Rodgers pointed out that 371 was in the alpha phase and there was only very doubtful evidence that instability could be observed; incorrect quenching might have caused suspicious behaviour. Quenching was necessary for the best creep resistance, but an alternative technique, recovery from hot working, was sought.

* A three-figure number is allotted to each grade or alloy, the first figure of which indicates how many elements are present in appreciable quantity. Thus the numbers 100 to 199 are used for nominally pure titanium, the numbers 200 to 299 for binary alloys, 300 to 399 for ternary alloys, and so on. In distinguishing grades of nominally pure titanium a series of numbers has been allotted, an increase in number corresponding to an increase in hardness and strength. The softest grade possible, i.e. iodide titanium prepared by the van Arkel process, would be termed titanium 100, while the numbers 120, 130, 150 and 160 have been given to successively stronger grades of commercial purity. For titanium alloys the last two figures indicate the two main alloying elements, thus: (1) aluminium, (2) chromium, (3) iron, (4) manganese, (5) molybdenum, (6) silicon, (7) tin, (8) vanadium, (9) zirconium. Titanium 240 would, for example, denote a binary titanium-manganese alloy, titanium 314 a ternary titanium-aluminium-manganese alloy.

The Fairey "Delta 2"

By R. L. LICKLEY, B.Sc., F.R.Ae.S., and L. P. TWISS

On February 14 this joint lecture was given to the Royal Aeronautical Society. We reproduce here the first part of the lecture, read by Mr. Lickley, devoted to design and construction.

The development of manned supersonic aircraft in this country suffered a setback at the end of the 1939–45 war, when it was decided that the use of manned aircraft would be too dangerous; however, more realistic views soon prevailed and, as a result, the ordering of such manned aircraft was considered in 1947 by the Ministry of Supply, and in our submissions to M.o.S. in 1949, we described the aircraft as having as its primary function "Research Flying at Transonic and Supersonic speeds up to M=1·5."

The background which led up to this submission is of interest, as it shows a logical line of development within the company.

In 1947, the company was developing the "F.D.1." at Stockport and scale models of it at Heston, in order to conduct vertical take-off experiments. The models were of advanced design, propelled by a rocket motor with twin combustion chambers controlled in pitch and yaw respectively by an automatic pilot. Information of behaviour in flight was telemetered to the ground.

In September, 1947, the company was asked if it could further develop the vertical take-off models to fly transonically after ground launching as part of the experimental programme. After consideration it became clear that, although the technique and experience of the V.T.O. models would be of great value, the experiments themselves would be of little use unless they were aimed at obtaining specific information on a layout representative of a typical possible piloted supersonic aeroplane. We, therefore, began a design study of such a piloted aircraft as a preliminary to the design of the pilotless models. Our first efforts resulted in a design of high sweepback on both leading and trailing edges, all-moving tip ailerons, conventional tailplane and twin engines in the fuselage fed from a nose intake ("P.1" layout).

This design was not proceeded with, but in February, 1949, we were approached by P.D.S.R. (A) (then Sir Harry Garner) and asked to consider an alternative design for a further supersonic research aircraft, preferably based on a single engine. We had, of course, by this time considerable background in the problems of designing such an aeroplane. We had developed the necessary new techniques of drag and performance estimation and had collected together what slender information there was on the stability and control characteristics of various configurations. We decided to begin our considerations afresh and, by the end of the year (December, 1949) had come to a firm proposal which differed very little from the aero-

Fig. 1—Aircraft with nose drooped

plane as it is flying at present, although pressure from various sources to make changes was at times very strong.

The design which evolved was a delta-wing plan form of aspect ratio 2, having a Rolls-Royce " R.A.5 " engine in the body with wing root intakes with frontal areas cut to a minimum and all possible excrescences removed. The major target and guiding principle in the whole design period was to get an aeroplane of minimum weight, with the smallest frontal and surface areas, while still remaining a straightforward aeroplane to handle in the air and on the ground, and yet at the same time large enough to house the " R.A.5 " engine and sufficient fuel to enable worthwhile flights to be made. As an indication of the design problems raised by this approach, the maximum clearance between engine and fuselage skin is less than 6in and within this space room had to be found for the main frames to which the wing is bolted.

Although the aerodynamic form was decided at an early period, the contract to build two aircraft was not placed until October, 1950 ; lack of money, priorities and other problems caused this hold up and almost immediately after the placing of the contract " super-priority " intervened and the need at Faireys to concentrate on the " Gannet " meant that a fully effective start was not made on the design work until the summer of 1952, and manufacture effectively began about the end of that year.

Little or no priority was given to the aircraft and, because of the demand on wind tunnel capacity for tests or service types under development, only very meagre and belated high-speed tunnel tests had been undertaken before the aircraft flew. In fact, some supersonic tests were only analysed after the aircraft had flown supersonically.

With that introduction, we can now consider the main features of the design.

Aerodynamic Design

(1) *Moderate Wing Loading*.—This was chosen to give good high-altitude performance, medium landing speeds and good performance from normal length runways.

(2) *t/c Ratio*.—This, at 4 per cent, is still one of the lowest flying and at the design date (1949), was the lowest known.

(3) *Tailless*.—The advantages of this layout were held to outweigh the reputed disadvantages and, when one considers the various tail layouts to be seen to-day, and the established need for fully variable tailplanes, the choice seems to have been the correct one, possibly more than anything else, because of the aerodynamic simplification produced.

(4) *Intakes*.—Side intakes were decided on, as it was felt that the structural simplicity and saving in weight, compared with a nose intake, were worth more to the design that the possible aerodynamic difficulties introduced. At various times the intakes were the subject of strong criticism, both from the aerodynamic aspects and from the possible bad effects on compressor flow, but they have remained substantially as initially conceived, and have proved satisfactory up to the highest Mach numbers reached.

(5) *Large Chord Controls*.—Much discussion has ranged round trim drag and the penalties it applies to delta aircraft. Our thinking led us to believe that much of the drag could be avoided by careful design and, in particular, by the use of large chord controls which would keep the angular movements reasonable. So far, our only problem with these controls has been lack of jack effort in certain flight cases ; as predicted, the effects of trim drag have not been serious.

(6) Mathematically defined forms were used for aerofoils and fuselage, to enable high accuracy of contour to be attained in the final manufactured product.

(7) *Dive Brakes*.—These, of petal form, at the rear of the fuselage, were designed to give minimum change of trim, &c., and in flight at sub- or super-sonic speeds have given no pitch or lift changes and more than adequate deceleration.

(8) *Body Form*.—Considerable work was done on this and it might be described as an early approach to area rule—the short intake fairings (inspired by Küchemann) combined with a cylindrical body to the trailing edge and the swept-fin mainly behind the trailing edge.

These, briefly, were the aerodynamic fundamentals of the design and the results obtained in the flying have shown them to have been soundly chosen.

Structural Design

The use of a very thin wing, combined with a fuselage almost full of engine, presented many difficult structural problems.

The thin wing (4 per cent) set the major problems and it was decided to use a form of construction in which the spars were perpendicular to the fuselage, with ribs or stringers parallel to the fuselage centre line. This shortened the length of the spars and greatly simplified the joints to the fuselage frames. The wing root bending moment, due to the small thickness, requires a number of spars, situated aft on the wing. Each spar is attached to machined fuselage frames which, to ease manufacture, were made in three pieces and this had the additional advantages of making the frame statically determinate.

The wing consists essentially of two torsion boxes, one at the leading edge and one, the major torsion box, between the chassis and the control surfaces which are cantilevered off the trailing edge of this box. The skins of this aft torsion box are of thick light alloy, the thickness being dictated by requirements of torsional stiffness. Except at the root, the wing skins carry practically all the wing bending loads, but at the side of the fuselage the loads in the skin diffuse out into the three main spars.

The fin is attached at leading and trailing spars in a manner similar to the wing. The main bending attachment was made integral at the root with a cross member, so that once the critical narrow base attachment had been made the introduction of backlash on the fin base through fin removal was rendered less likely, as the detachable attachments were on a wide base. The main fin skin thickness was determined by stiffness requirements for the avoidance of flutter.

The rear fuselage forward to the break joint (seen in Fig. 2) is of monocoque construction and has the petal brakes mounted on it. The problems of mounting the petals have the feature which is reproduced many times on this aircraft, i.e. the difficulty of incorporating into a small space mechanism dealing with large loads.

The centre fuselage consists of heavy frames connected by longeron members ; the frames take the wing loads and support the engine.

The cockpit, which droops to provide improved view for landing, provided another difficult problem as almost the entire top of the cockpit has to be open to provide for seat ejection, &c. This problem was dealt with by building the relatively open cockpit on to a complete box forward of the forward bulkhead of the cockpit. The cockpit, when in the up position, is attached to the front fuselage by a conventional set of latch pins.

The control surfaces are constructed with a heavy leading edge torsion box designed by stiffness, and a light trailing edge designed by strength considerations. Provision was made for mass balancing, but this has not been needed.

A point of interest is that the structure weight was 1 per cent less than the weight estimated in 1949.

Flutter

Very full and careful flutter investigations were made and only a summary can be given here.

Calculations made early in the design stage showed that with the expected impedance of the hydraulic jacks actuating the control surfaces, the addition of mass balance made little difference to the flutter speed of the wing-aileron combination. The results are shown on Fig. 3, the jack impedance being above 1×10^6 lb-ft/rad.

Later calculations by the Multhopp-Garner theory confirmed this view and showed that the addition of mass balance could bring in a low flutter speed if it caused the control surface natural frequency to be reduced to two-thirds of its value with no mass balance.

In view of these results and the fact that mass balancing would add considerable weight to the aeroplane, it was decided to eliminate it from the aircraft.

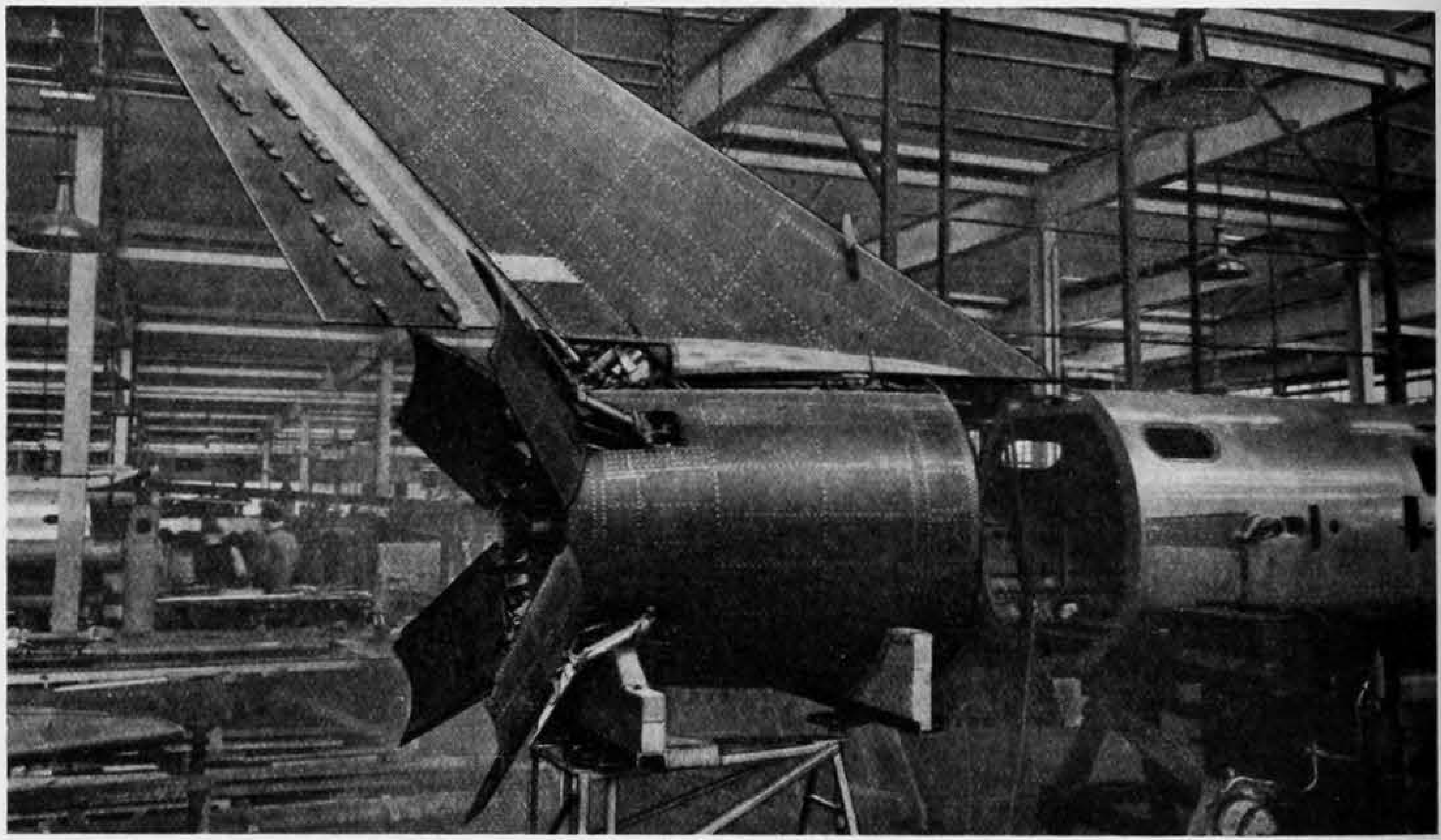

Fig. 2—Rear fuselage, showing dive brakes extended and fuselage break

This has helped in the avoidance of transonic control surface buzz and single-degree of freedom flutter by keeping the natural frequency of the controls as high as possible. Other favourable factors are the very small trailing edge angle and the large chord of the control surfaces. It has not been found necessary, so far, to fit hydraulic velocity dampers to increase the control surface damping in the transonic region.

Very full flight testing (described in greater detail later) has confirmed this approach, stick tapping having been carried out throughout the full flight range. The responses obtained from stick tapping appear to be sufficiently accurate to confirm the policy of flight vibration testing by this method and, since the taps have been capable of exciting nodes at 35 c/s, it was felt that it was not necessary to use other methods. The use of this method has meant that a large number of records have been obtained in a comparatively short period. The analysis of the results indicates only slight variation of damping with Mach number.

General Design Considerations

The thin wings and small fuselage, already referred to, provided the over-riding design factors but a further point was kept well to the forefront and that was, so to design the aircraft that easy maintenance and straightforward servicing were provided. This approach has paid high dividends, giving what has been described as " airline reliability " and permitting up to six flights per day.

Design matters of interest are :

(1) *The Drooping Nose.*—With the need to keep the height of the windscreen to a minimum and yet give the pilot adequate view at the high angles of incidence at landing, various schemes such as retractable seats, &c., were studied but the final, and the simplest, solution was that of drooping the nose portion containing the pressure cabin. This is hinged on the bottom longerons and is operated by a hydraulic jack. It is a light and straightforward means of giving the pilot better view and has been reliable in operation. It did, however, set up some problems connected with the jettisoning of the hood. To ensure that the hood would jettison correctly, it was desired that it should pivot about an aft hinge on release. This pivot point, however, could not be earthed on to the fuselage, due to the drooping of the nose including the hood. This was overcome by having two " barrow handles " carrying the aft pivot points, tipping with the droop nose and lying flush in troughs in the main fuselage in the nose-up position : these can be seen in Fig. 1. To keep the drag to a minimum, the hood was designed with very small clearance from the pilot's head and is kept flush with the surrounding structure by having hinges on one side, thus avoiding sliding mechanisms which would increase the difficulties of pressure sealing.

(2) *The Main Undercarriage.*—This was a geometric, as well as a mechanical, problem. It was found that levered suspension was the most satisfactory manner of absorbing the required energy with the short length of leg at our disposal and that this would also most easily fit the very limited area and thickness available in the wing housing.

The wheel, when housed, lies in a plane parallel to the inner surface of the upper wing skin. To rotate the wheel into this position the top of the leg is attached by means of a universal joint to an inclined rotating eyebolt, while a side bracing member forms a secondary hinge and controls the path of the wheel during retraction, and a telescopic fore-and-aft member takes the drag. The eyebolt is mounted on a boss on the spar forging.

(3) *General Servicing.*—In line with the policy mentioned earlier this had considerable study and, along the fuselage, a top deck was provided to carry all control rods, electrics, hydraulics, filters, &c., and this has proved invaluable for easy servicing.

(4) *Engine Installation.*—The engine is a Rolls-Royce R.A. series engine with reheat. The basic engine is standard, some small external changes being made to enable it to fit our fuselage.

With the exception of reheat problems in the early stages, there has been little trouble with the power plant, in spite of tight clearances, and the general reliability has been high.

The engine is fitted or removed by breaking down the rear fuselage near the fin and sliding the engine out on rails on to special ground equipment. This has enabled engine changes to be made easily and without breaking any services other than to dive brakes and rudder.

(5) *Hydraulics and Power Controls.*—These have been left to last in the description of the design, although great care and forethought were devoted to them and throughout the whole period of flying they have given every satisfaction.

It was decided in the early days to use power controls of Fairey manufacture, as we were just beginning to manufacture these in quantity and felt that our equipment had many advantages over anything currently available elsewhere. The further decision was taken to duplicate fully the control system and to do without manual reversion. As a result, the aeroplane has fully-powered, fully-duplicated controls, with Fairey valves and " Hydroboosters." To eliminate flutter tendencies as far as possible, the jacks are attached to solid structure and the valves operated by push-pull rods, to keep break-out forces to a minimum.

There are two hydraulic pumps driven by the engine, one of which feeds a main accumulator which powers the flying controls. The second pump feeds a second accumulator which supplies power not only to the flying controls, but also to the main and nose undercarriage retraction mechanism, the droop nose, and the air brakes. In addition to these accumulators, there is an emergency accumulator which can be selected to power either the flying controls or the other services and there is also a brake accumulator.

In the event of an engine or hydraulic pump failure, an emergency air-driven turbine pump feeding the second system can be lowered into the air stream.

The air brakes are also operated by similar methods and the four petals are synchronised to ensure even opening. Another problem here was to operate the petals without excrescences and this was achieved by a system of floating links, giving a good moment arm, but remaining flush when closed.

Manufacturing Problems

This aircraft was our first attempt at building from solid without any transitional experience of similar types of construction. As a result, many detail problems arose in the manufacture but, by careful jigging and making full use of the solid frames and spares, we consider that the wing profile was made to a measured accuracy of $\pm 0\cdot005$in relative to the mathematical form laid

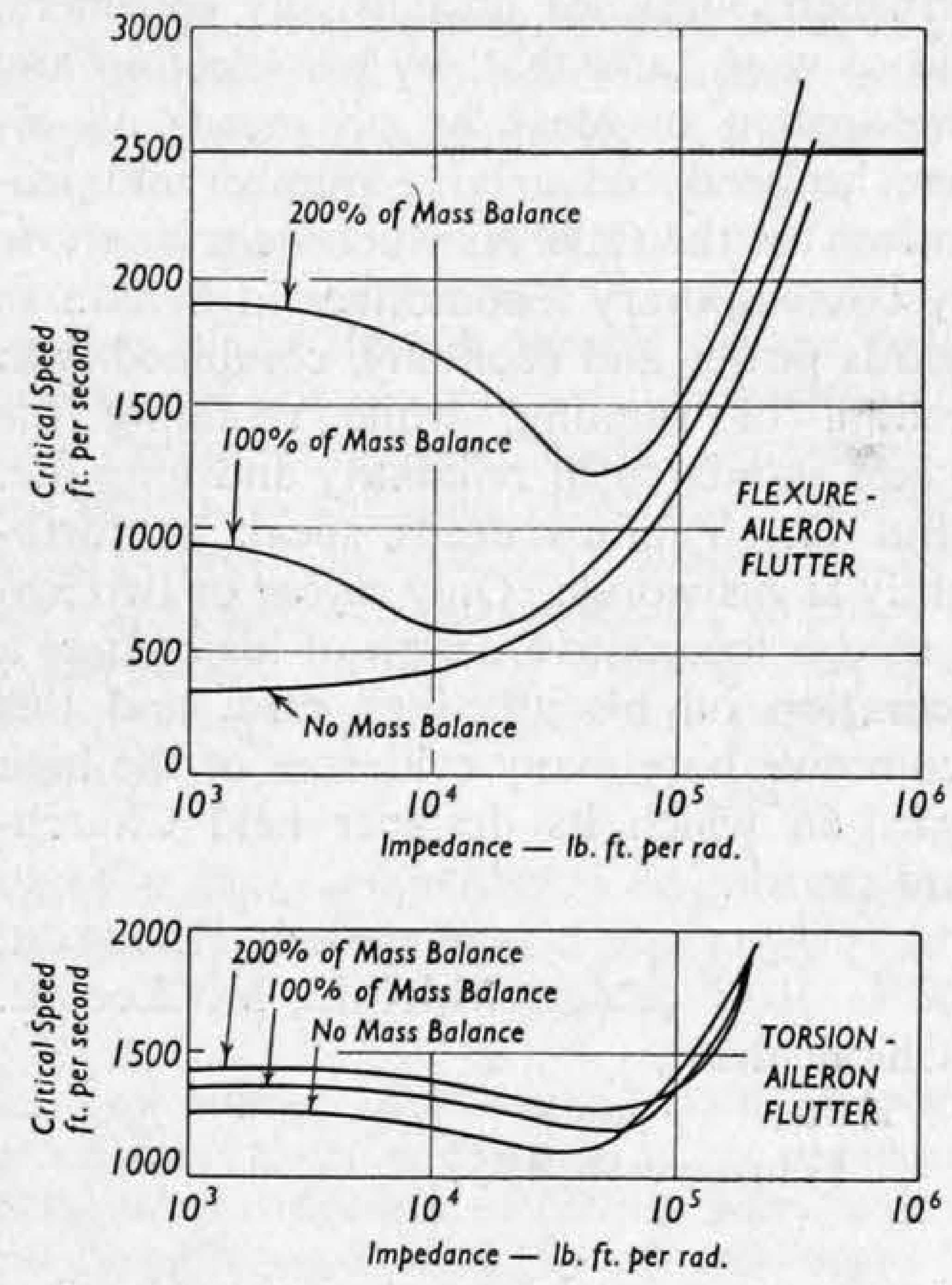

Fig. 3—Effect of aileron mass balance

down. In addition, the wings are attached to the fuselage by ten close tolerance fixing points and full interchangeability of wing to fuselage was provided.

Integral fuel tanks occupy most of the wing and their development was closely studied. It was finally decided to assemble the wing as a dry structure, designed and manufactured to be as fuel tight as possible in this state and subsequently sealed by slushing. This system has worked out very well in practice.

In spite of the major machining problems of the spars and frames from rough forgings, and the assembly difficulties of the thin wings and fin, the aircraft flew about twenty months from the start of construction. It is worth noting that the last three months were mainly involved in inspection, testing of systems, impedance testing and general preflight work, an indication of the complexity of the systems.

Finally, with all these problems behind us, the aircraft made its first flight at Boscombe Down on October 6, 1954.

Discussion

Mr. F. W. Page agreed with the authors that the 60 deg. delta was an attractive starting point for a supersonic design. On a warplane with a large disposable load, however, the limitations of c.g. travel and the large aft movement of c.p. at the highest speeds became obtrusive. A " notched " planform, imagined as having the elevators and the part of the wing in front of them moved aft to form an all-moving tail, more nearly avoided these problems and gave better damping in pitch : there was not undue difficulty in this solution. He pointed out that many of the stability tests involved trimming the aircraft into a positive *g* manœuvre at supersonic speeds : the restrictions on flight over this country hampered the flying programme seriously, while testing over the sea was excessively risky. Mr. Lickley agreed that a place where supersonic flight could be performed was badly needed : he thought that the problem of where to locate a tail plane was severe.

Mr. R. A. Shaw, remarking that whether there would be any aircraft like the F.D.2 in future was open to question, suggested that the machine would be used to establish a correlation between wind tunnel and free flight observations. He expected that supersonic flying would have to be done in foreign air space.

Wing Commander McDonald inquired whether the designers of the F.D.2 had benefited from the ten years' experience of supersonic flight previously accumulated in the United States. Mr. Lickley said that very little information about this work had been available in this country.

Sir George Edwards drew attention to the statement that little or no priority had been given to this important project. Whatever the reason why the record had not been challenged, the fact that it had stood for nearly a year would offset the unfavourable impression created by the report of a Select Committee.

In answer to a further question, Mr. Twiss related that the automatic observer photographed sixty instruments at intervals of up to two seconds.

Mr. L. W. Rosenthal observed that a " revolutionary " aircraft had been built in twenty-six months : was this because of the two years that lapsed after the contract was placed ? Mr. Lickley explained that it was because the designer's decisions did not alter.

Mr. J. L. Cooper wondered whether sonic " bangs " would be frequent in, say, twenty years' time : Mr. Twiss explained that it was only the early development flying that it was desired to do over land.

Group Captain G. Slade considered that there was enough testing outstanding to occupy the aircraft for two and a half years. He pointed out that only seven pilots had flown either of the machines, and two of them had only five flights between them : there was a pressing need for more such machines to extend the experience of the pilots. For these reasons it was not acceptable that they should be grounded frequently by bad weather : flight testing should be performed in a favourable climate, at least during the English winter.

(At the meeting Mr. Twiss described the flying of the " Delta 2 " near Bordeaux in France : he had made high-speed runs along the line of the coast, while the phenomena of sonic " bangs " were recorded on the ground. It was remarked that the technicians involved in these tests lived in the towns over which the aircraft flew at speed : they were, to say the least, tolerated.)

Institution of Naval Architects.—The spring meeting of the Institution of Naval Architects will be held in the Weir Lecture Hall, 10, Upper Belgrave Street, London, S.W.1, on March 26, 27 and 28, when the following will be the programme. Tuesday morning, March 26, the annual general meeting, followed by paper No. 1, " Iron Ore Carriers," by Mr. James Lenaghan. The annual dinner will be held in the evening at Grosvenor House. Wednesday, March 27; in the morning, paper No. 2, " Ship Hydrodynamic Laboratory," by Dr. J. F. Allan, and paper No. 3, " Effect of Cavitation on the Performance of a Series of 16in Propellers," by Dr. R. W. L. Gawn and Professor L. C. Burrill. In the afternoon, paper No. 4, " Methodical Series Experiments with $0\cdot70$ Block Coefficient Forms " : Part I, " The Effect on Resistance and Propulsion of Variations in L.C.B. Positions," by Mr. R. E. Blackwell and Mr. G. J. Goodrich, and Part II : " The Effect on Resistance of Variations in Breadth Draught Ratio and Length Displacement Ratios," by Mr. R. E. Blackwell and Mr. D. J. Doust, and paper No. 5, jointly with the Institute of Marine Engineers, " Further Sea Trials on the 'Lubumbashi,' " by Professor G. Aertssen. Thursday, March 28, in the morning, paper No. 6, " The Interaction between a Ship's Hull and a Long Superstructure," by Dr. J. C. Chapman ; paper No. 7, " Stresses in Deckhouses and Superstructures," by Dr. A. J. Johnson, and paper No. 8, " The Effect of Superstructures on the Longitudinal Strength of Ships," by Dr. J. B. Caldwell, and in the afternoon, paper No. 9, " The Conditions for Unstable Rupturing of a Wide Plate," by Mr. G. M. Boyd, and paper No. 10, " Ship Hull Pressure Measurements," by Dr. N. Hogben. The morning meetings will begin at 10.15 a.m., and the afternoon meetings at 2.30 p.m.