A SIMPLE MECHANICAL SOLUTION

SKI JUMP

BY

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There are those who would claim that mechanical engineering has reached a plateau of development, that the scope for new ideas lies in other fields. One purpose of this article is to expose the fallacy of this line of thought, another is to demonstrate the virtues of the simple approach. The title is a little misleading because 'mechanical' implies the existence of moving parts and the device which is the subject of discussion has none. That is the ultimate in simplicity. Simplicity in this instance, as in most perhaps, is only skin deep. It is simple in application, to the user; to the designer it is a complex interaction of constantly changing factors and this is what makes it interesting because nothing new is involved except the idea. There are no new discoveries, no breakthrough in materials, just a new combination of ancient principles. There remains plenty of scope for new combinations and creativity in mechanical engineering.

A solution implies the existence of a problem. Often the problem is one of long standing, openly acknowledged and keenly felt. The arrival of the solution is hailed with rejoicing and its creator acclaimed as a benefactor. If the problem lies in the future or, for one reason or another, is not acknowledged, then the inventor of the solution faces a lonely and frustrating struggle for he must first convince the customer of the existence of the problem and the customer may be unwilling to admit deficiencies in existing equipment or methods—he has enough difficulties already. The problem which provides the subject of this article fell into the latter category.

The problem

The problem is to find a means of improving the take-off performance of fixed-wing Vertical/Short Take Off and Landing (V/STOL) aircraft in general and of the Sea Harrier for the Royal Navy in particular. At this point the customer (if you can capture his attention) asks, 'Why?' The aeroplane can take off vertically, this is a feat remarkable in itself, an engineering triumph, why ask more? It must be borne in mind that the aircraft cannot take off vertically (VTO) at a weight greater than its thrust, due to a fundamental law of physics. In fact because of intake losses and factors such as the download created by the airflow induced by the downward pointing jets, the Harrier aircraft lift off vertically at a weight of only about 85 per cent. of the engine test bed thrust. The word 'only' is belittling in this context and this is unjust because in a VTO the Harrier lifts half its capacity disposable load of fuel plus ordnance and this is a tremendous achievement. For comparison a conventional aircraft at its minimum take-off distance, which is far from vertical, carries by definition, zero disposable load. Nonetheless the Harrier can lift vertically only half its maximum load and the goal must be to exploit all its load carrying ability to make it fully effective as a military weapon.

The customer (wearying by now) points out that by using a Short Take Off (STO) the Harrier can lift its full capacity load from a take-off run which is a small fraction of that of an equivalent conventional aircraft and which is within his capacity to provide. Once again, why ask more? At this stage it becomes clear that the real problem is the customer.

Why Ask More?

The short answer is 'in order to operate more efficiently'. Efficiency in this context can be interpreted in terms of cost effectiveness or military effectiveness. For maximum operational effectiveness the Sea Harrier will be operated in the Short Take Off, Vertical Landing (STOVL) mode in which it is launched in a STO at high weight and on return from its sortie, with stores expended and most of its fuel consumed, is recovered by vertical landing. The vertical landing requires a deck space only a little larger than the maximum dimensions of the aircraft, but the STO requires a deck run of up to 600 feet. This is deck space which must be dedicated solely to Harrier take off. It cannot be used, except temporarily, for anything else. If the take-off distance can be reduced, then the deck space available for other purposes can be increased, giving the ship more operational capability. Alternatively a smaller, and therefore cheaper, ship can be used. For either reason the objective is a worthy one especially if it can be attained at low cost. The customer at last begins to show interest and asks, 'How?' The answer is to use the simple mechanical solution. It is called Ski Jump and it radically improves the STO performance of fixed-wing vectored-thrust V/STOL aircraft. An appropriate starting point for an understanding of Ski Jump principles is the basic STO launch.

STO Launch

The aircraft starts its take-off run with jet nozzles essentially horizontal, accelerating along the flight deck until the bow end of the deck is reached when the pilot rotates the nozzles downwards to an angle, typically, of 50°. At this point the thrust vector has a vertical as well as a horizontal component and since the deck edge has been passed it is clearly essential that the vertical forces on the aeroplane equal its weight if it is to remain airborne. The situation is shown in FIG. 1; the force polygon indicates that most of the sustaining force is provided by deflected thrust with aerodynamic lift making a relatively small contribution. A digression here to explain a Harrier peculiarity. The high-speed jet efflux entrains large quantities of the surrounding air and induces an increased airflow around the aircraft. When the jet efflux is directed downwards this induced airflow naturally has a downward component which reduces the effective wing incidence and hence lift. As a result, there is little or no aerodynamic lift at speeds below about 50 knots, but at higher air speeds aerodynamic lift increases at a rate of approximately 66 lb per knot of airspeed (2). This explains why a Harrier operating in hover or VTOL gains nothing from wind over deck (WOD).

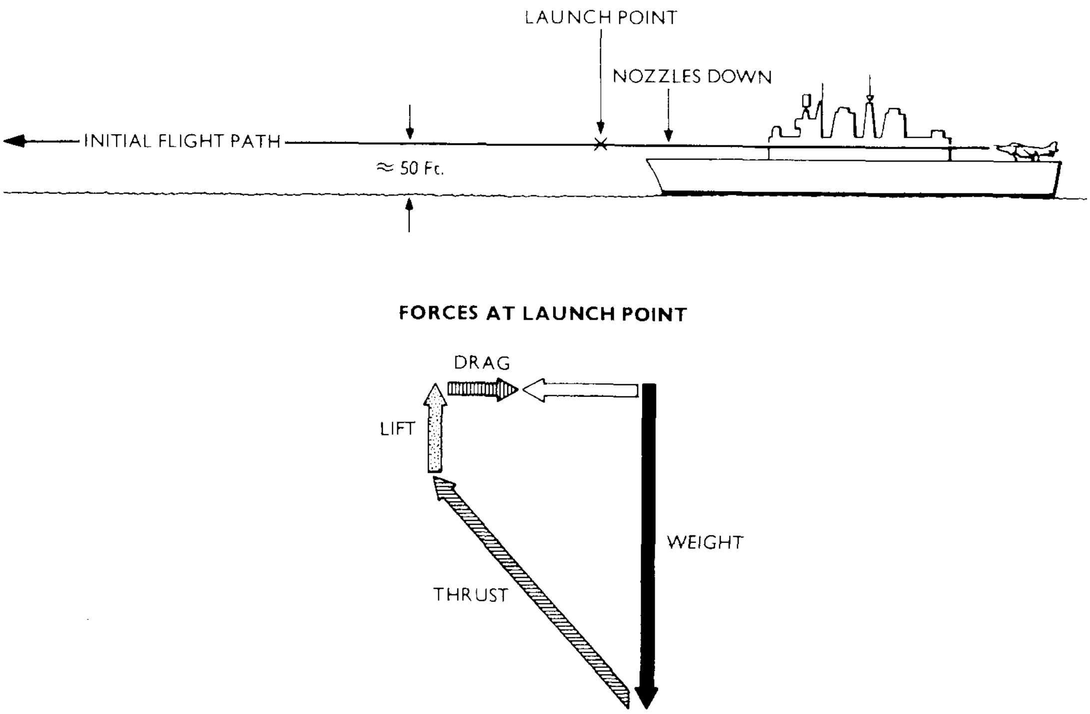

FIG. 1 – STO LAUNCH

Returning to the STO, the aircraft has left the deck at an airspeed of, say, 100 to 130 knots and its weight is supported by a combination of the vertical component of engine thrust and aerodynamic lift with the latter contributing only about 15 to 30 per cent. This point in the take off is called the Launch Point. At this point the force polygon shows that the horizontal component of engine thrust exceeds drag and so the aircraft accelerates gaining aerodynamic lift at the rate of 66 lb/knot. As lift is gained the pilot can progressively rotate the nozzles aft towards the horizontal until transition to wholly wing-borne flight is completed. The Launch Point, marking the start of transition to conventional flight, is important and should be kept in mind.

The length of the STO run depends on the speed required at the end of the flight deck to provide the aerodynamic contribution of lift and is proportional to launch speed squared. It follows that a relatively small reduction in the end speed required gives a large reduction in take-off distance. Very considerable reductions in launch speed can be achieved by the use of a semi-ballistic launch technique.

Semi-Ballistic Launch

Imagine the aircraft at the same weight and configuration (nozzles deflected downwards) as the aircraft at the STO Launch Point, but with two vital changes in its circumstances. These are:

(*a*) Instead of leaving the deck horizontally the aircraft leaves at an upward inclined angle so that its velocity has a vertical as well as a horizontal component. For the moment, the means of achieving this condition are ignored.

(*b*) Its speed is much lower than the flat deck STO launch, there is very little aerodynamic lift and, since weight is unchanged, it follows that there is a lift deficiency.

This lift deficiency gives the aircraft a vertically downward acceleration which may be expressed as:

$$\dot{V} = -\frac{g}{W}\left[W - \mathrm{T}\,\mathrm{Sin}\,(\theta + \gamma) - \mathrm{L}\right]$$

where:

$\dot{V}$ = vertical acceleration
g = acceleration due to gravity
W = aircraft weight
T = engine thrust
θ = jet deflection angle relative to aircraft datum
γ = instantaneous flight path angle relative to horizontal
L = vertical component of aerodynamic lift.

The downward acceleration continuously modifies the trajectory of the aircraft so that it curves towards the horizontal. A typical trajectory with force polygons for various points on the trajectory is shown in FIG. 2. The downward acceleration itself changes through the trajectory. At launch the force polygon shows a large vertical thrust component and very small aerodynamic lift and drag forces. There is sufficient thrust along the instantaneous flight path to accelerate

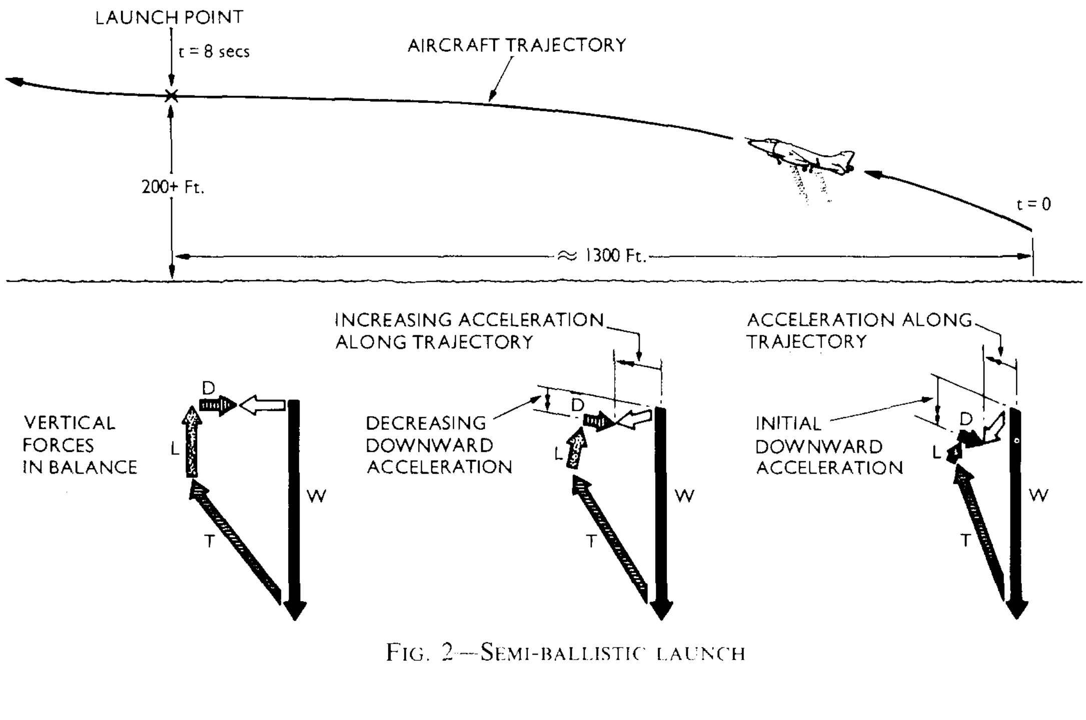

FIG. 2—SEMI-BALLISTIC LAUNCH

the aircraft. A few seconds later γ has decreased, the vertical component of thrust has, in consequence, decreased slightly. On the other hand, the flight path aligned component of thrust has increased giving more acceleration and L is increasing rapidly as a consequence of the increasing airspeed. At the peak of the trajectory the lift forces and the weight of the aircraft are in balance, the flight path is substantially horizontal and the aircraft is at the Launch Point, but this has occurred some 8 seconds later, 1300 feet further from the ship and (very important) 200 feet or more higher than the same state in a flat deck STO launch.

A simple summary of the principle is that the aircraft is launched into an ascending ballistic trajectory like a shell from a gun. This ballistic trajectory provides a finite time of flight which is used to accelerate the aircraft, under its own thrust, to a speed at which sufficient aerodynamic lift is generated to sustain the aircraft.

Continuing the gun analogy, the trajectory of a shell has a descending as well as an ascending part and it is clear that more time of flight can be gained and hence a lower launch speed if part, at least, of the descending trajectory is also utilized, always provided that the Launch Point is arranged to occur at a safe height above the sea. Such an extended trajectory is shown in FIG. 3 and is certainly practicable, but the additional reduction in launch speed is less than might be expected. This is because the aircraft acquires a downward momentum, during the descending part of the trajectory, which must be destroyed in order to curve the flight path back towards the horizontal. The vertically upward force required to destroy this momentum is in addition to that required to support the aircraft weight and must be provided by the wings because the engine is already at full thrust. This means that additional airspeed is required. The concept of this switchback trajectory is more theory than reality because, for good practical reasons, aircraft are not launched at the theoretical minimum speed; a safety margin is added which in this case means that the aircraft would, in practice, start transition at the peak of the trajectory as in FIG. 2 and the trajectory in FIG. 3 would be an emergency case. Having absorbed the basic principles the trajectory must next be examined in a little more detail for it is a thing of exquisite subtlety.

Analysis of Trajectory

It can be shown (1) that the theoretical trajectory can be calculated from the following two expressions:

$$\dot{V} = \frac{g}{W}\left[T \operatorname{Sin}(\theta + \gamma) - W + \rho \frac{S}{2}\sqrt{u^2 + v^2}\,(C_L u - C_D v)\right]$$

and,

$$\dot{U} = \frac{g}{W}\left[T \operatorname{Cos}(\theta + \gamma) - \rho \frac{S}{2}\sqrt{u^2 + v^2}\,(C_L v + C_D u)\right]$$

where:

$\dot{V}$ = instantaneous vertical acceleration
$\dot{U}$ = instantaneous horizontal acceleration
v = vertical component of velocity
u = horizontal component of velocity
ρ = atmospheric density
S = characteristic area
C_L = lift constant
C_D = drag constant

For a particular aircraft, e.g. the Sea Harrier, the trajectory will be modified by other factors such as engine thrust characteristics and the induced airflow effects already mentioned which make the practical performance fall short of theory. Nonetheless the results are sufficiently close for generalized conclusions to be drawn.

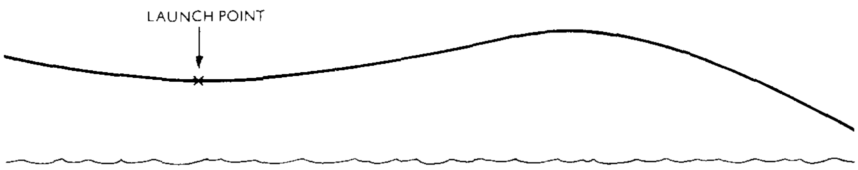

FIG. 3—EXTENDED SEMI-BALLISTIC TRAJECTORY

The most important variable is the initial launch angle. The effects of varying this while keeping W and θ constant are shown in FIG. 4 which plots minimum launch speed for a Launch Point at the peak of the trajectory against launch angle for three different weights. Obviously there is very little to be gained by increasing launch angles beyond 45° and, in fact, the bulk of all possible advantage is obtained at much more modest angles. For example 20° gives about 70 per cent. of the maximum possible reduction in launch speed. The curves also show why a vertical catapult (which is occasionally mooted) is far from being the best method of launching V/STOL aircraft.

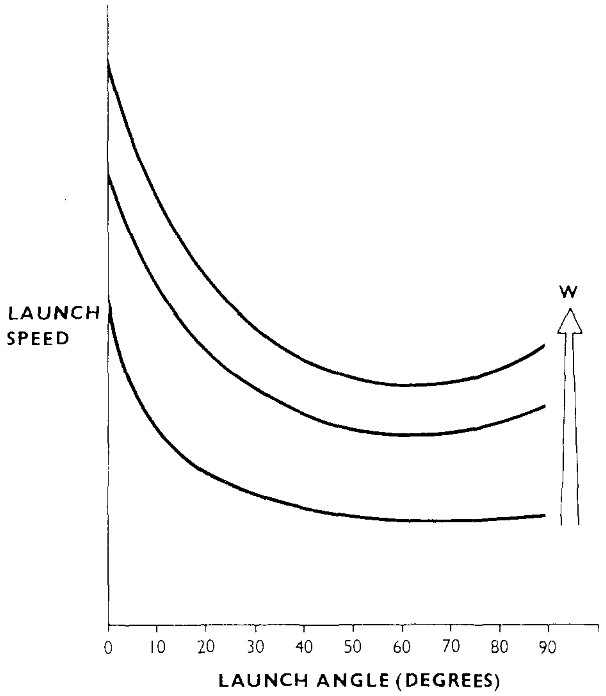

FIG. 4—LAUNCH SPEED V LAUNCH ANGLE

As noted earlier, the take-off distance varies as launch speed squared and from FIG. 4 the main advantage of the semi-ballistic launch can be deduced—that is the dramatic reduction in take-off distance required. This varies with aircraft weight but over a typical range of operating weights a launch angle of 20° gives reductions of 55 to 70 per cent. in STO take-off distance.

The other important variable is the nozzle angle (θ) and it can be shown (1 and 3) that there is, in fact, an optimum nozzle angle which depends on aircraft weight and launch angle as indicated in FIG. 5.

Having dissected the semi-ballistic trajectory, the next problem is how to achieve it; to find a means of launching the aircraft at an angle to the horizontal. The use of some form of inclined catapult springs naturally to mind and is entirely feasible. It would give absolutely minimum take off distances (about one aircraft length or less) but would involve extensive modification of a Sea Harrier and the development of a suitable catapult. We are looking for a simpler solution and so we come, at last, to the Ski Jump.

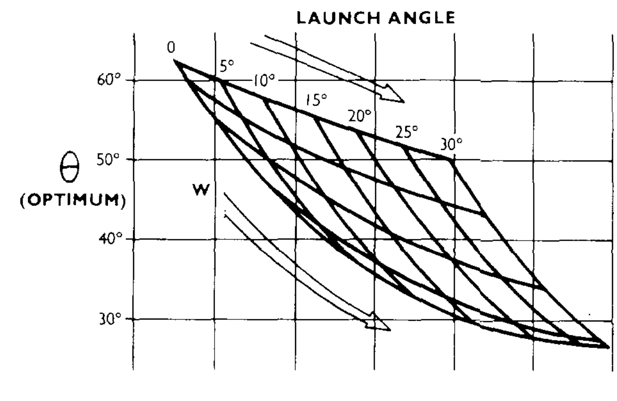

FIG. 5—OPTIMUM NOZZLE ANGLE

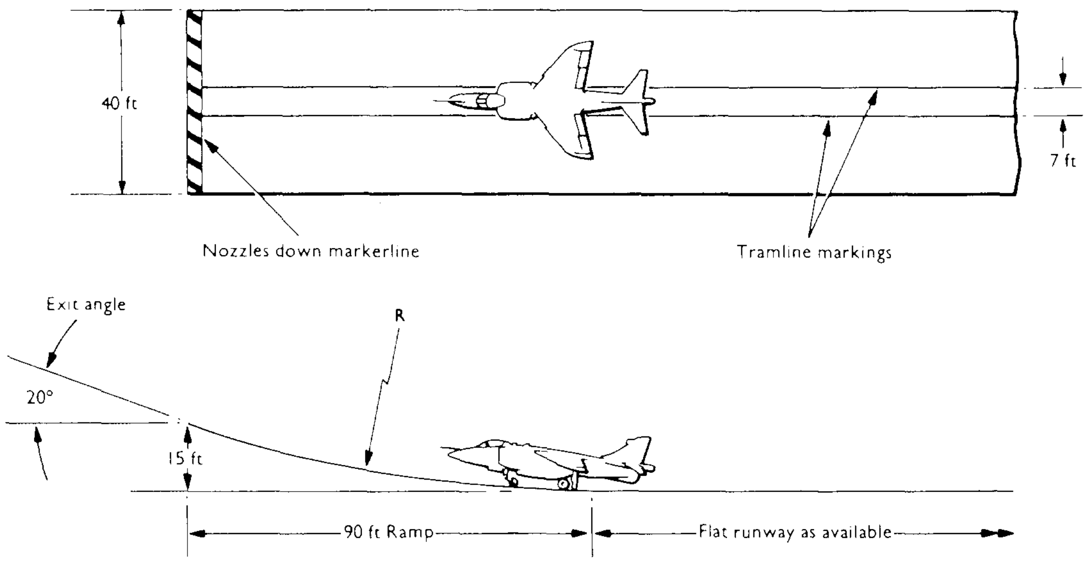

FIG. 6—THE SKI JUMP

The Ski Jump

This is shown diagrammatically in FIG. 6. The Ski Jump take off follows exactly the same procedure as the flat deck STO. The aircraft accelerates with nozzles horizontal along a short flat runway which leads into a gently curved ramp. Near the top of the ramp the pilot rotates the jet nozzles through the preselected angle θ and the aircraft continues into the semi-ballistic trajectory already examined. Naturally the acceleration of the aircraft up the curved ramp is a little less than its acceleration on the level; however, elementary calculation shows that the difference in launch speed compared with a flat-deck launch from the same starting point is very small (typically 2 to 4 knots in 60 knots) at ramp exit angles of about 20° and the net result is that the Ski Jump take off distance is much less than that required from a flat deck. The very considerable reductions in deck run are shown in FIG. 7. Wind over deck is beneficial to all STO launches and a more complete picture of operating conditions is shown in FIG. 8.

The experienced engineer is liable to feel the first stirrings of disquiet at this point in the story. There is a distinct flavour of 'something for nothing', there is no mention of penalties nor can any obvious penalty be discerned and all his instincts reject this unnatural situation. A fundamental penalty exists in fact, but

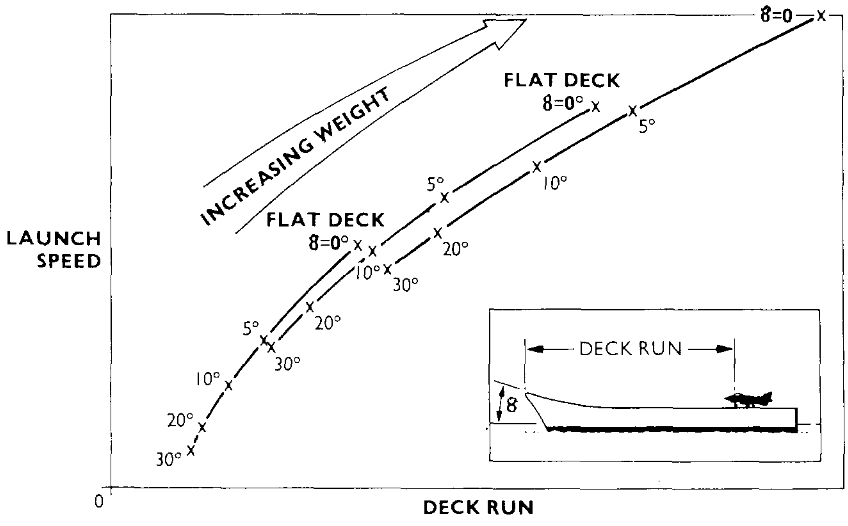

FIG. 7—SKI-JUMP TAKE-OFF DISTANCE (NO WIND)

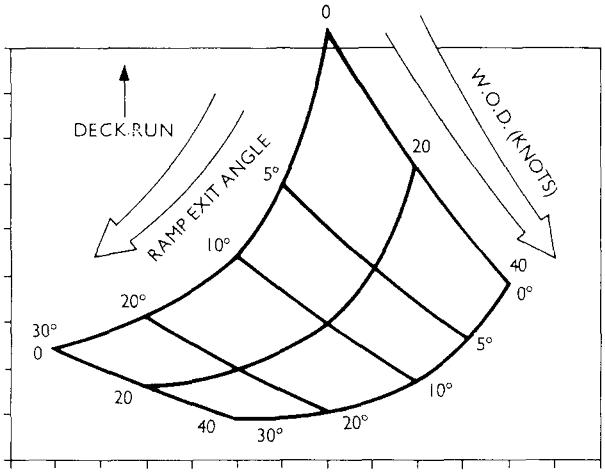

FIG. 8—SKI-JUMP LAUNCH—EFFECT OF W.O.D. (TYPICAL STO WEIGHT)

it is painless. It becomes evident if the take-off distance is considered to be the distance from the start of the take-off run to the Launch Point. In the flat deck STO the Launch Point is just clear of the bows of the ship, typically 500 feet to 600 feet from the STO starting point. The Ski Jump launch in the same conditions requires typically 250 feet of deck run and the Launch Point is 1300 feet from the end of the ramp (FIG. 2). The total take-off distance for the Ski Jump launch is therefore 1300 + 250 = 1550 feet—about three times as long as the flat-deck STO. This is the penalty, but 1300 feet of this 1550-foot 'flight deck' is made of air. We have only to provide 250 feet of steel deck. There are other penalties associated with Ski Jump and we shall come to them, but first let us consider its advantages.

Ski Jump Benefits

Apart from the reduction in deck take-off distance which is its *raison d'être*, the Ski Jump displays other beneficial charateristics. The most important of these is improved safety. Comparison of FIGS. 1 and 2 shows how this occurs. The semi-ballistic trajectory with its initially ascending flight path removes an imminent source of danger, the proximity of the sea, at a time when the pilot is busy and concentrating on precise control—indeed it removes the necessity for *precise* control in the early stages of the launch. The additional height is, of course, a safety factor in the event of a serious malfunction such as an engine failure, because the time available for the pilot to recognize the emergency and, if need be, abandon the aircraft, is approximately trebled.

Another important benefit arises from the fact that the semi-ballistic Ski Jump launch can be shown to be much less sensitive than the flat deck STO to ship pitching motion (3). This is a safety factor and is also a performance advantage since a smaller margin of launch speed needs to be added to the Ski Jump launch than to the flat deck STO, again decreasing take-off distance or obviating the necessity to reduce payload in high sea states. In fact, at a launch angle of about 20 , any ship motion which permits movement of aircraft on deck at all may be ignored. Thus two important benefits of Ski Jump are complementary: the reduced take-off distance allows aircraft operation from smaller ships than has hitherto been possible, and the insensitivity to ship motion counteracts the liveliness of the smaller ship in a seaway.

These advantages are obtained by the use of a device which contains no moving parts and is conventionally constructed of cheap structural steelwork. The ship-fitting problems are minimal compared with the simplest of catapults; the ramp could be pre-fabricated, swung on board and welded or bolted in position. An integral structure designed as part of the ship in construction involves a negligible weight penalty. The Ski Jump benefits may, therefore, be summarized as follows:

Greatly improved take off performance.
Low cost. Reliability. Improved safety.
Less affected by ship motion.

Now the problem areas and limitations must be considered.

Problems and Limitations

These arise almost entirely from the undercarriage characteristics of the Sea Harrier which was not designed for Ski Jump launching. The undercarriage was in fact designed to meet a R.A.F. requirement for rough ground operation which is, in some ways, much more demanding than the Ski Jump launch, but which results in an undercarriage which is not ideally suited to this type of launch even though its basic mechanical strength is adequate.

When the aircraft traverses the curved ramp it is rotated in a nose-up direction through an angle of, say, 20° in rather less than one second so that just before it leaves the ramp it is rotating in pitch at about 15 to 20 degrees/second. Now the Harrier has a bicycle type undercarriage with the nose and main undercarriage legs separated by about 12 feet so that when the nosewheel leaves the ramp the centrifugal reaction from the curved ramp is transmitted to the aircraft by the main undercarriage leg which is aft of the centre of gravity. This causes a nose-down pitching acceleration which, in the short time taken to move 12 feet and bring the main wheels clear of the ramp, largely cancels the nose up pitching velocity. At first sight, therefore, the designer has merely to cope with the loads generated by centrifugal force which are a function of the speed of the aircraft and the radius of curvature of the ramp. However, the undercarriage legs must be considered as spring systems and, returning to the start of the ramp, we find first the nosewheel (well ahead of the C.G.) imparting a vertical force closely followed by the main wheels (behind the C.G.) applying a vertical force a little later. The result is the start of a pitching oscillation and there will also be an oscillation in the heave sense. The natural frequency of both oscillations is about 1 Hz so that there is not quite sufficient time for the aircraft to complete one cycle on the ramp in most typical cases. The sum of these effects is the occurrence of peak loads on the undercarriage legs some 30 per cent. in excess of those to be expected from centrifugal loading (4). This sequence of events is fixed and, in theory at least, it should be possible to smooth the peaks by suitable variation of the ramp profile. Motion on the ramp is illustrated in FIG. 9.

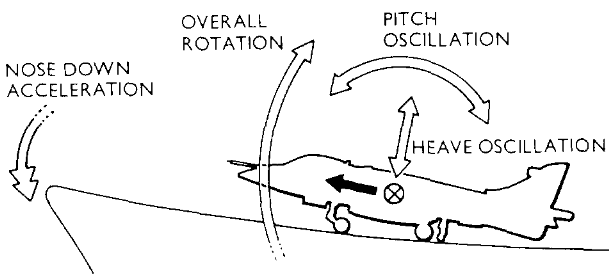

FIG. 9—MOTIONS OF AIRCRAFT ON RAMP

There is another event which unfortunately has no precise position in the launch sequence and which introduces some unwelcome complications: it is the rotation of the jet nozzles by the pilot. The timing of this depends on the pilot's reactions and there is considerable scatter. Nozzle rotation may occur near the beginning of the ramp, near the end or at any point in between. In one respect it has a beneficial effect in that the perpendicular component of thrust relieves undercarriage leg loads. The thrust is applied through the C.G. and so the consequent behaviour of the aircraft will depend on the characteristics of the main and nose undercarriage legs. As it happens, the nose leg has much less rebound damping than the main and so the effect of rotating the nozzles is to rotate the aircraft about the main wheels, i.e. nose up, and could result in the aircraft leaving the ramp with an inconsistent nose-up pitch rate if nozzle rotation occurs at an unfavourable point in the pitching cycle (4).

It can be seen that the motion of the aircraft at launch is the result of a complex interplay of forces and factors such as speed and ramp shape and size. Speed depends on ramp exit angle and aircraft weight; if speed is fixed within limits then the shortest ramp possible is desired. For a given launch angle, short ramps demand a short radius of curvature which puts up centrifugal loads and exacerbates the oscillation problem. Theoretical studies (4) have shown that to cope with varying conditions a ramp of circular arc profile is an acceptable compromise and that to keep the ramp within reasonable dimensions (about 100 feet long) undercarriage modifications will be required for ramp exit angles exceeding 6 . Fortunately the modifications required are relatively simple. The first is a reduction of the rebound rate of the nose leg by fitting a smaller orifice in the recoil damper. This will alleviate the pitching induced by nozzle rotation and take the maximum launch angle up a few degrees. The next stage of modification could involve increasing the gas pressure in the main leg to avoid bottoming under peak loads and an increase in tyre pressures. (Tyres are low pressure for rough ground—not required for deck operations.) These modifications are relatively inexpensive since no structural alterations are required and will take the Harrier to launch angles of 20° or possibly a little more and this is likely to be the practical limit for the Sea Harrier for some time to come.

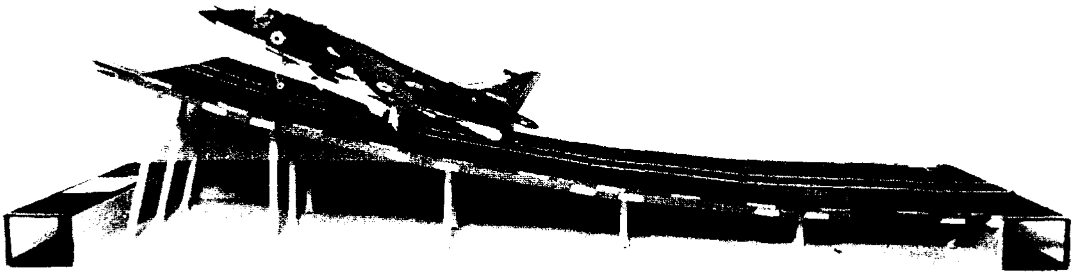

FIG. 10—THE TRIALS RAMP (EXIT ANGLE 20°) MODEL

Ski Jump Development

By the time this article is published initial flight trials of the Ski Jump will be completed. These are aimed primarily at a handling assessment of the aircraft in semi-ballistic flight and confirmation of the predicted dynamic behaviour of the aircraft on the ramp. The potential performance gains have been confirmed by the extensive computer studies and simulations conducted by the Kingston Design Team of Hawker Siddeley Aviation Ltd., and are not in doubt. The trials ramp (FIG. 10) is built on a runway at RAE Bedford and its exit angle is variable between 6 and 20 . The ramp profile can also be altered from the basic circular arc. These variations are obtained by the use of a number of hydraulic jacks to support the ramp. The shipboard ramp which will be produced using the results of these trials will be a fixed structure. It is anticipated that flight trials up to the maximum ramp angle will be completed within one year.

Ship Shapes

Ski Jump, like the angled deck, impinges on the ship designer's world because it alters the shape of his ship, though it should cause him much less headache than the angled deck with its big overhangs. It must be emphasized that ship and aircraft are part of an integrated system and should be treated as such. There is plenty of scope for ingenuity here and readers may care to exercise their own.

FIG. 11 shows a straightforward application by professional ship designers. It is Vosper Thorneycroft's conceptual design for a Harrier Carrier with a 6° Ski Jump. The Ski Jump is almost insignificant, a gentle, seamanlike sheer which enhances the appearance of the ship and gives its Sea Harriers the same performance from its 420-foot deck run as they would have from *Invincible*'s much longer flat deck. The next two pictures may serve for further stimulus though they are the sketches of an amateur. FIG. 12 is a DLG-sized vessel which utilizes the reduced flight-deck requirements to put flight deck and hangar on the same level thus eliminating lifts. Aircraft lifts are structurally undesirable in a

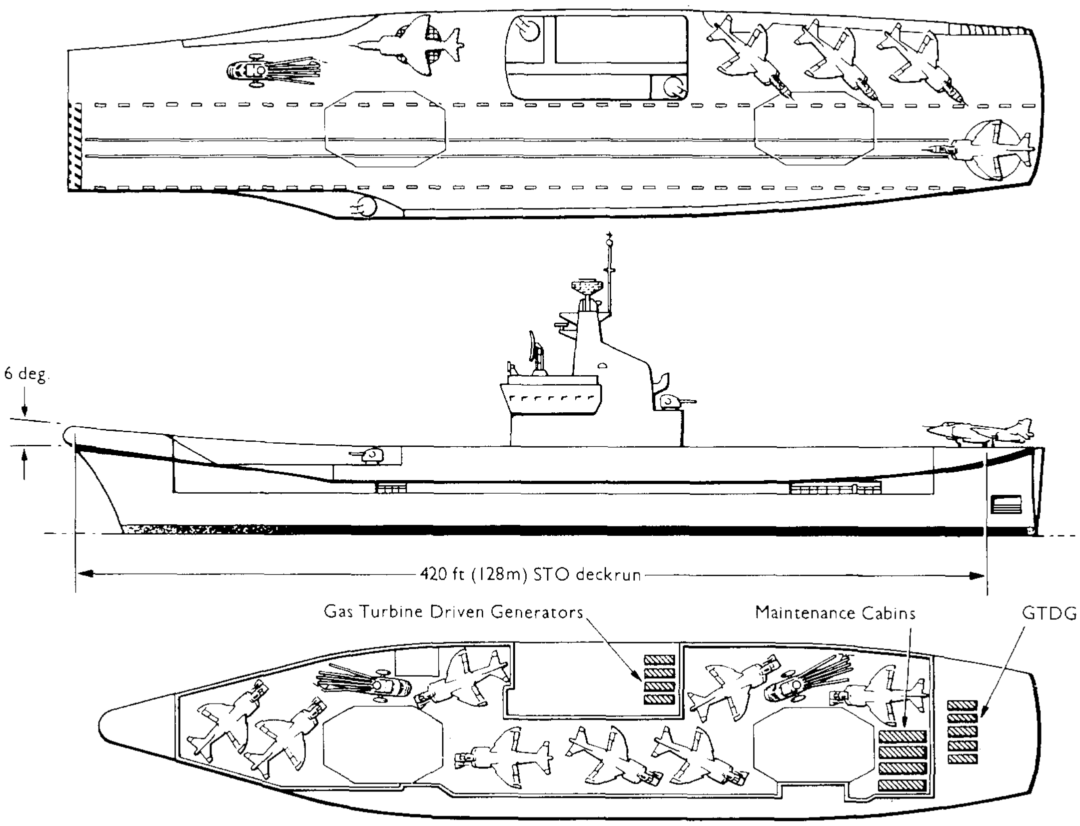

FIG. 11—GENERAL ARRANGEMENT OF THE VOSPER THORNYCROFT DESIGN FOR A HARRIER CARRIER

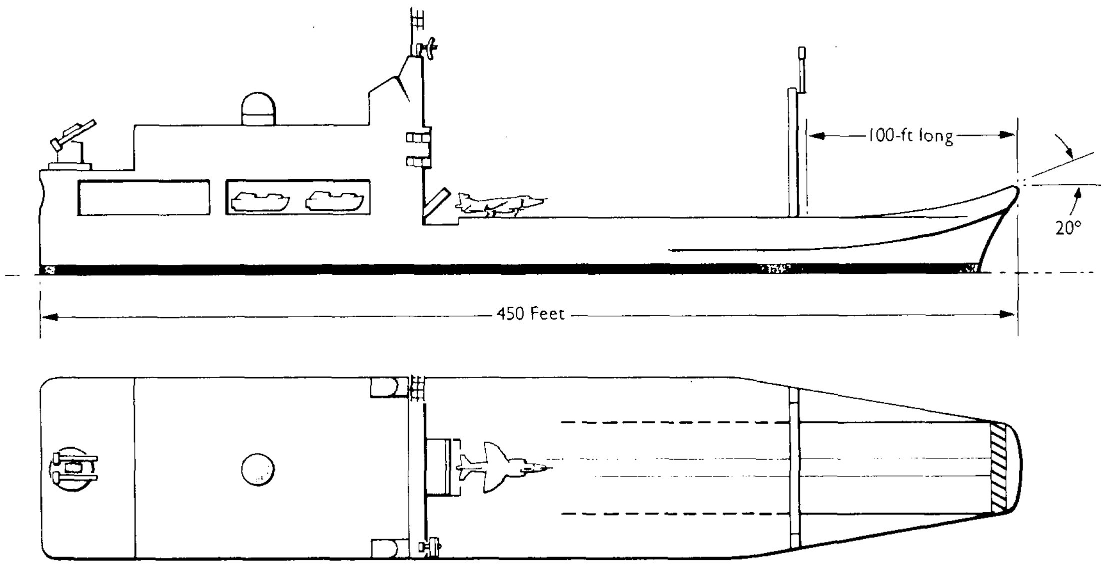

FIG. 12

small hull and waste space because a lift occupies space equivalent to at least two aircraft. FIG. 13 is a rather more ambitious cruiser with a split-level layout in which the Ski Jump ramp is made to serve also as a lift by means of a power-operated hoist built into a flush track in the ramp.

Another fertile field for the amateur designer is the provision of a quick conversion kit for a supertanker or container ship to enable it to operate Sea Harriers and helicopters and the ultimate perhaps is to build the capability of operating a Sea Harrier into a frigate.

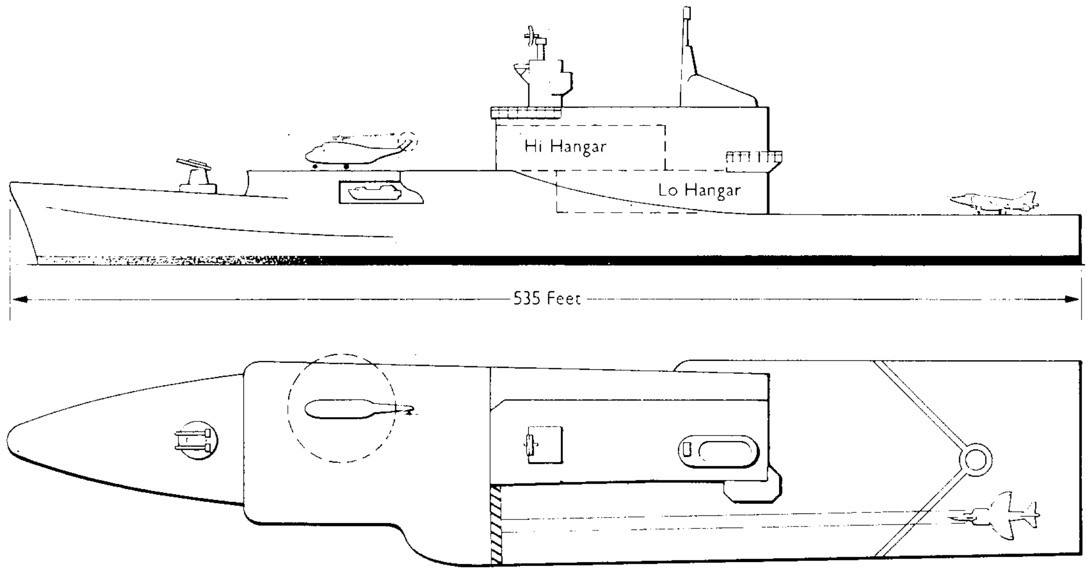

FIG. 13

Conclusion

The Ski Jump surely demonstrates that the simple approach need not lack intellectual challenge and that the achievement of simplicity is a worthwhile and demanding objective. The benefits of simplicity are obvious and Ski Jump provides a first-class example. The performance improvements could have been gained by other means: more thrust from the engine, more lift from the wing or by using a catapult. Any of these would have cost several millions of pounds over a period of five to ten years. Active Ski Jump development will have taken just over two years to completion and cost £250 000. It is gratifyingly appropriate that the Ski Jump should be so closely involved with the V/STOL Harrier. V/STOL has always been an extremely demanding objective when combined with a requirement for effective military payload. The Harrier has achieved its success only by the exercise of ingenuity, in broad concept and in detail, towards the only effective means of meeting the target—simplicity.

Acknowledgement

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