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A Simulator Study of Direct Lift Control

By

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SUMMARY

The report describes a fixed base simulator study of direct lift control as applied to the VC 10 aircraft. The practical limitations imposed by factors such as the small spoiler authority to control lift, the power control dynamics, and the c.g. range over which the system must operate are included. A degree of improvement in longitudinal handling can be obtained from DLC, but it seems from this work that the most promising arrangement lies in a combination of DLC and a 'manoeuvre boost' input to the elevator. Confirmation by flight trials of the improved performance in the landing flare is needed, because of the difficulties of simulating this phase of flight.

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* Replaces A.R.C.32 826

CONTENTS

INTRODUCTION

In the past few years, several research workers have predicted that as aircraft size increases, a point will be reached where conventional methods of longitudinal control are no longer satisfactory. Difficulties will occur, it is said, both because the pitch response associated with the large pitch inertia is sluggish, and also because the period of the short period oscillation is long. In consequence, considerable lags will occur in changing the flight path of large aircraft, if this is achieved in the usual way by means of pitch attitude changes. To add to the difficulties, elevator down-lift effects could also be significant for large aircraft with a relatively short tail-arm.

Fortunately, the theoretical understanding of stability and control problems of aircraft is well advanced, and proposals to alleviate these shortcomings have been made. Of particular interest is the use of a fundamentally new form of longitudinal control, in which lift is commanded directly by the pilot's stick, without changing the attitude of the aircraft. This system, direct lift control (DLC), and the underlying theory, is well described in reference 1. The report is mainly concerned with the basic principles of how best to employ DLC - to define the optimum point of action of the lift force, to predict its influence on speed stability, and to assess the influence of DLC on stalling behaviour. In the report, the concept of control lift moment arm, K_η is introduced, and it is shown that a powerful relationship exists between K_η and manoeuvre margin H_m, in the design of an optimum DLC system. In fact the theoretical optimum point at which the lift should act is such that $K_\eta = -H_m$.

The aircraft designer cannot easily provide direct lift. The two most promising methods are either the use of fast acting flaps, or the use of partially extended spoilers. Neither of these devices is likely to produce lift at the optimum point as defined above. It is also clear that the optimum point of action of DLC is a function of c.g. position, and so ideally, the point of action should be variable. Other practical difficulties which arise concern the magnitude of the incremental lift force which either spoilers or flaps can provide, and the associated (and unwanted) pitching moments.

Because of these considerations, any practical application of DLC must supplement rather than replace the conventional pitch control. Systems have been flown (reference 2) in which the pilot has been given independent control of pitch and DLC. Other flight tests have covered the case of gearing the DLC to the elevator, thus leaving the control layout unchanged as far as the pilot is concerned (reference 3).

It is clear therefore, that the successful use of DLC rests on practical considerations, such as the c.g. range of the aircraft, the lift devices available, the authority of these devices, aerodynamic non-linearities, and so on. It is also necessary to determine whether or not pilot opinion supports the hypothesis that the longitudinal control of aircraft will be substantially improved if the lag between control application and change of flight path is removed. The provision of good handling qualities is a complex and elusive task - many a plausible theory has foundered on the rocks of flight experience.

The work described in this report was intended to answer some of these questions. An attempt was made to simulate a practical DLC installation in a large aircraft. The characteristics of the system, in terms of response to a step control input, were examined at different flight conditions and c.g. positions. From these responses, the most promising arrangements were evaluated by pilots in a fixed base simulator.

2. REPRESENTATION OF AIRCRAFT

The choice of the Super VC10 as a basis for the investigation is justified for several reasons. It is a large, modern transport aircraft, and the lateral control system incorporates spoilers. These could be modified to take symmetrical DLC inputs, should an in-flight research programme be undertaken at a future date. All the data to describe this aircraft are readily available; much of the aerodynamic description is based on flight measurements. Pilots familiar with this aircraft could be called on within BAC. Finally, the VC 10 configuration is reasonably representative of future, larger aircraft, and so the results may be applied to them with some confidence.

The description of the VC 10 as used in the simulation is contained in appendix 1. The simulation was valid over a range of ± 60 knots relative to the datum speed of 138.5 knots. The longitudinal aerodynamics were represented by C_m, C_L, and C_D curves, rather than by quasi-static derivatives. The appropriate changes to these coefficients due to change in position of flaps, spoilers, and c.g. position were included, as were the effects of wing stall. Simple representation of power control actuator dynamics, in the form of first order lags, was made.

The assumed forward c.g. position of 18% $\bar{c}$ corresponded to a manoeuvre margin of +.41, and a static margin of +.32 $\bar{c}$. The aft c.g. of 36% $\bar{c}$ corresponded to $H_m = +.23\bar{c}$, $K_n = +.14\bar{c}$. The spoiler lift acted at a position 2% $\bar{c}$ ahead of the neutral point (50% $\bar{c}$).

3. SYSTEM LAYOUT

The introduction of DLC into an aircraft control system will modify the normal acceleration response. It is useful to compare the idealised normal acceleration response obtained from a direct lift control with that obtained from a conventional elevator control (fig. 1 a). If the DLC is applied at the aerodynamic centre, a normal acceleration response of the type seen in fig. 1 b is obtained. Applying the DLC at a distance ahead of the aerodynamic centre equal to the manoeuvre margin, the response of figure 1 c results. A similar normal acceleration response can be obtained, if instead of applying the DLC at this optimum point, the DLC and elevator are geared together. (This, in practice, is a preferred arrangement, because the position of the direct lift device is no longer critical). With DLC applied at the aerodynamic centre, the pitch attitude of the aircraft will change in the conventional sense, and pilots will adapt more easily to this new form of control. The gearing of DLC to elevator is a function of DLC position and c.g. position. The selection of this gearing is presented in Appendix 2.

A further consideration arises from the limited control power which is available from spoilers. In the case of the VC 10, by setting the spoilers in the mid position (25°), a maximum incremental g of $\pm$ 0.12 is available by fully opening or closing the spoilers. If the spoilers are geared to the elevator, changes in speed or normal acceleration (for example, as experienced in turning flight) will rapidly erode this control margin. The simplest way to overcome the difficulty is to 'd.c. block' the control input, so that steady control deflections result in a 'zero' position of the lift producing device. The optimisation of any DLC system must take into account the effect of such a device. A simulator study at RAE (reference 4) has indicated that the 'd.c. blocking' time constant should lie between 2 and 5 seconds. For all the work reported here a value of 4 seconds was used. The influence of d.c. blocking on the step response is seen on figure 1 d.

The next factor to consider is the response of the spoiler and elevator drive system. Any actuation lag or rate limit will influence the response to a step input. For the purposes of this study, the actuator dynamics were represented by a first order lag of 0.2 seconds time constant. The effect of this lag may be seen typically on figure 1 e. Comparing figure 1 e with 1 c, it is clear that the design aim of DLC, to achieve immediate lift, and to sustain it at the same level, is compromised by practical considerations.

One way out of this difficulty is to apply transient elevator inputs which will 'fill-in' the troughs in the normal acceleration response of figure 1 e. The layout of such a system is seen on figure 2. The stick input is fed both to the spoilers and to the elevators via d.c. blocked electrical paths, in addition to the mechanical stick to elevator gearing. The choice of the blocking time constant and gain of the elevator 'boost' input determine how well the troughs are filled. For the work reported here, unity gain and a 1 second time constant were assumed, again based on earlier work at RAE (reference 5).

This latter addition, in which elevator inputs are supplemented by a transientised elevator signal, has been used in the past to improve the longitudinal response of aircraft, independent of DLC. It is often referred to as "manoeuvre boost" (MB). A pitch rate feedback term is sometimes added to the elevator signal, so that both the stability and response can be adjusted. The combination of DLC and manoeuvre boost affords good opportunities to tailor the longitudinal response to a desired standard. Fig. 1 f shows a typical response with manoeuvre boost alone, and Figure 1 g shows a combination of DLC and manoeuvre boost.

Finally, it must be emphasised that a manual control system cannot be designed solely on the basis of normal acceleration response to a step input. Equally important is the response in pitch. For both physiological and psychological reasons, a control system which produces either excessive pitch transients, or negligible pitch initial response will find pilot disfavour. The results to be presented therefore include both pitch and normal acceleration response. To summarise, the control systems which together formed the basis of the investigation were:

1. DLC

$$\text{Spoiler angle} \quad \Delta\delta_s = 25^\circ + \frac{1}{1 + 0.2s}\left[G_1 \cdot \frac{t_1 s}{1 + t_1 s} \; \delta_{e_{\text{pilot}}} \right]_{\pm 25^\circ \text{ limit}}$$

where $t_1 = 4.0$ seconds

and $G_1 = -8.9$ deg/deg

The value of the gearing G_1 is calculated in Appendix 2.

2. Manoeuvre Boost (MB)

$$\text{Elevator angle} \quad \eta = \frac{1}{1 + 0.2s}\left[\eta_{\text{pilot}} + G_2 \; \frac{t_2 s}{1 + t_2 s} \; \eta_{\text{pilot}} \right]$$

where $t_2 = 1.0$ seconds

and $G_2 = 1.0$ deg/deg

4. RESPONSE TO STEP CONTROL INPUTS

A large number of responses to step pitch control inputs were obtained for the basic aircraft, the aircraft with DLC, and the aircraft with DLC and MB. They covered the forward and aft c.g. positions, speeds of 120, 138.5, 160 and 180 knots, and all the flap positions for which trimmed flight was possible (fig. 7). In character, they are all very similar, and it is only necessary to reproduce in this report typical examples. Fig. 8 shows the response to a 2° step elevator control input of the three control configurations listed above, for the 138.5 knots, 45° flap case. The responses at the forward and the aft c.g. positions are presented.

At the forward c.g. the DLC improves the normal acceleration response quite markedly. The effect of elevator downlift is eliminated, 0.07g is rapidly achieved, followed by a 'droop' in response after about 1.5 seconds. The combination of DLC and MB completely removes this droop. The pitch response is also of interest. In all cases the pitch response is in the conventional sense, but the DLC system gives appreciably less rate of pitch during the first four seconds than the other two systems.

For the same control input, the steady normal acceleration is almost doubled at the aft c.g. Because the gearing of spoiler to elevator is unchanged, the influence of DLC is not so marked as in the forward c.g. case. The droop in normal acceleration is again apparent, with DLC alone. The combination of MB and DLC gives a substantially improved normal acceleration response over that of the basic aircraft.

Figures 9 and 10 tell substantially the same story at a lower speed, with full flap, and at a higher speed with reduced flap angle. They confirm that over a reasonable range of approach speeds, in spite of the associated changes in short period dynamics and elevator angle per g, the fixed geared DLC + MB system provides the same degree of improvement in response as that obtained at the design datum condition.

The remaining question is whether a more careful choice of gearing might give a better compromise between the responses at forward c.g. and aft c.g. positions. Perhaps by increasing the gearing, overgearing at the forward c.g. might be acceptable, in order to improve the aft c.g. case. That this is not so, at least for the VC 10, can be seen on figure 11. The stick / spoiler gearing has been doubled, which represents a value near to the optimum at aft c.g. The forward c.g. normal acceleration responses reflect this over-gearing, for both the DLC and DLC + MB cases. Note also that the pitch rate is initially negative for DLC alone case: a characteristic which will appear to the pilot as a nose drop, or 'nod'. Unfortunately, the aft c.g. cases are also disappointing. Particularly worrying is the droop in the normal acceleration response for both the DLC and DLC + MB cases. The initial negative pitch rate can be seen on the DLC trace, as in the forward c.g. case. It is likely that by doubling the MB gearing as well as the DLC gearing, better results could be obtained for the DLC + MB case. However, the combined adverse effects of droop and nod suggest that only minor increases in gain could be tolerated for the pure DLC system.

5. DETAILS OF SIMULATION

5.1 Computing

Large perturbation equations of motion were used to describe the longitudinal characteristics of the VC 10; small perturbation equations of motion were used for the lateral characteristics. The appropriate kinematic equations included the effects of speed and wind shear. To solve these equations, an analogue computing capacity of about 200 amplifiers, with various non-linear computing elements were needed. The mild turbulence was pre-recorded, and played back into the equations of motion of the aircraft.

The ILS was simulated on a small digital computer. This allowed precise computation of the position of the aircraft relative to the glide slope to be made. It also allowed accurate computation of the angular errors in elevation and azimuth, for ranges from touchdown between 50,000 feet and 500 feet. Since these signals form the basis of the pilot's task, accurate computation is necessary.

The digital computer was also used to record and to analyse the pilot's performance.

5.2 Cockpit

A fixed base cockpit was used, into which a two-handed control column was fitted. Neither the instrument layout, nor the stick/rudder pedal geometry corresponded exactly to those of the VC 10. However, the primary flight instruments were simulated - ASI, attitude horizon, compass, V.S.I., altimeter, slip ball, and ILS meter. Also the force/deflection characteristics of the stick and rudder pedals were closely matched by the mechanical/hydraulic feel system. The throttle and tailplane trim controls were on the left hand console in the simulator; additionally, a pitch trim button on the stick, could be used, if the pilot found the position of the tailplane trim inconvenient. (In the actual aircraft, pitch trim is achieved from a rate trim switch on the throttle console. Trim inputs do not change the stick position). Selectors on the left hand console allowed the pilot the choice of flap position, DLC, and MB. Flap operating time was the same as on the aircraft. Selection of MB caused the spoilers to move to the mid position, taking ten seconds. The corresponding changes in lift, drag and pitching moment were simulated.

5.3 Display

The visual display was given by a closed circuit TV/model system. The model, on a continuous belt, is to a scale of 1,000:1, and covers an area of countryside 6 miles by 2 miles, full scale. The maximum visibility is 2½ miles. The 625 line monochrome TV picture is collimated. The cloud-base was set at 300 feet throughout the experiment. The model includes a 6000 feet runway, and approaches down to touchdown are possible.

5.4 Task

The pilot's primary task was to fly an instrument approach using raw ILS down to 100 feet. At 100 feet he transferred to the visual display, for the final approach, flare and touchdown. Mainwheel touchdown was indicated aurally to the pilot. Parameters to measure performance both on the glideslope and at touchdown were recorded, at ranges less than 10,000 feet (500 feet height on the glide path). The original intention was that the azimuth and elevation errors would be measured at four 'gates' at equal intervals down the glide-slope. However, the preliminary trials showed that the errors at a given gate, as well as depending on the form of control system, were dependent on chance factors, such as the gust input at a given time, and that the error at the gate was unlikely to be representative of the error over a time interval around the gate. In consequence, a large number of approaches with each pilot for each control system would have been necessary to obtain a statistically significant answer to the question "which control system gives the best performance". The preferred method was to record the elevation and azimuth glide slope errors at 90 points on the glide slope, each 90 feet apart, between ranges of 10,000 and 2,000 from touchdown. From these errors, the mean error, mean modulus of error, and standard deviation were computed. Errors at a gate 1000 feet from touchdown were also recorded.

The approach was started from an initial range of approximately 5 miles, with no track error, at a height of 1500 feet. Ample time was available for the pilot to select the control configuration, intercept the glideslope, and stabilise on it before any 'scoring' began.

Two quite arbitrary choices were made in selecting the scoring method. First, the elevation and azimuth errors which were recorded were the angular errors on the glide slope - not the displacement errors. The reasoning behind this choice is that the pilot is trying to null angular errors, and so an analysis based on such errors is a better measure of his performance. Secondly, errors were only recorded during the last 45 seconds of the approach, from 500 feet down to 100 feet. The justification is two fold. Errors have a greater significance to the pilot during the last 500 feet. Also, the ILS indication of error is very insensitive at long ranges, and virtually excludes the evaluation of subtle control system changes.

5.5 Recording and analysis

The parameters which were recorded in the digital computer are shown on figure 12 . From the 90 glide-slope angular error signals were computed mean error, mean modulus of error, and standard deviation. The computation was made automatically after touchdown, and stored. At the end of a set of runs, the results were printed out by the teletype. The results for one run of a typical set are also shown on figure 12. Unfortunately, a minor programming error caused occasional print errors in the 'range at touchdown' data. These results have, therefore, been omitted in the next section. Otherwise the method of recording and analysing worked very well; to have accumulated and processed the same data by analogue methods would have been very tedious.

Analogue trace records were made however, of all piloted approaches. They proved to be most useful in understanding a given set of digital results, particularly in conjunction with the pilots' comments.

After each approach, the pilot noted particular aspects of the approach and flare, on a standard comment sheet. The particular comments asked for were i) I.L.S. (easy, consistently high, chasing, etc.) ii) flare success (sink rate at touchdown estimate, touchdown point long/short, etc.) iii) general remarks. The pilot was asked to record whether good (or bad) performance in a particular approach could be attributed to the form of control, to his own performance, or perhaps to some other factor, like a distraction.

6. RESULTS

The purpose of DLC is to allow better performance to be achieved, both on the glide slope and during the landing flare. It is important, therefore, that attention is given to the accurate measurement of performance in any study of this type. The criterion on which this measurement should be based is one question which arises - for example, is mean modulus of error a better basis than standard deviation? A more difficult question is to decide how many approaches in a given configuration are necessary before one is reasonably sure that the control system and not the pilot is causing the measure of performance to change. If all the approaches were made by one pilot, a sufficient number of trials could be made to give a high confidence level to the results. The doubt would then arise as to whether the results could be generalised to apply to all pilots.

Another question, particularly relevant to simulator work, is the background of simulator experience which is necessary before valid answers are obtained. Is it even possible that too great a familiarity with the simulator leads to a control technique which is effective in the simulator, but less effective in flight? And yet we rely very much on pilot comments. A system which gives good performance but adverse comments is certainly not the optimum. The comments must be made in the knowledge of the simulator limitations, and must try to project the simulator experience into real flight.

The ten pilots taking part are all highly experienced, but had varying familiarly with the Warton simulator (they were from BAC Warton, BAC Weybridge, and RAE Bedford). Each pilot was allowed to fly each configuration until he felt that his performance was reasonably consistent, before recorded approaches were made. Also, to offset learning effects, the control systems were evaluated in the reverse order by some of the pilots. No noticeable differences due to this change were seen.

It should also be observed that the pilot knew the configuration he was flying. The investigation was intended to look at a practical installation of DLC. It would have been impossible to disguise the fact that the DLC system acting through the spoilers increases the drag, and requires a more nose up attitude for trimmed flight at a given speed. In all probability, the convenience of pilot selection of configuration (thus allowing rapid comparisons to be made) added more to the results than any 'pilot pre-judgement factor could subtract.

Each pilot made three approaches for the three control systems - basic aircraft, DLC, and DLC + MB, at the forward c.g. position. At the aft c.g. position, three approaches were made with four control systems - basic aircraft, DLC, MB, and DLC + MB. The extra configuration was tried only at the aft c.g. because it is at the aft c.g. that the greatest scope for control system improvement lies. The results for all the pilots are seen on table 1 to table 7. Listed on these tables are the values of parameters printed out by the digital computer.

Tables 1 to 7 were used to produce histograms of the mean error, mean modulus of error, and standard deviation of error on the glideslope, at the forward and aft c.g. positions. These histograms are presented on figures 13, 14, 15 and 16 . A similar analysis of the 'sink rate at touchdown' results produces the histograms of figures 17 and 18 , for the forward and aft c.g.

cases. The sink-rate data were also used to produce figures 19 and 20 , which show the probability of achieving a given rate of sink at touchdown.

7. DISCUSSION OF RESULTS

7.1 Glide Slope Performance

Three measures of performance on the glide slope are available. Looking first at mean error (figures 13 and 14) it is possible to see a small improvement at the forward c.g., with DLC, and with DLC + MB. The improvement is more marked at the aft c.g., although the differences between DLC, MB, and DLC + MB are not immediately obvious. It must be remembered, however, that a pilot may prefer to fly an ILS one dot high and steady, rather than induce perturbations around zero in which case mean error is a poor yardstick. Mean modulus tells much the same story as mean error (figures 13 and 14), although the improvement in performance afforded by DLC and DLC + MB at the forward c.g. is much more marked. At the aft c.g., it appears that DLC alone gives the best results.

The histograms of standard deviation (figures 15 and 16) show DLC + MB in the best light, at forward c.g. At the aft c.g., there is little to choose between DLC, MB, and DLC + MB - all are better than the basic aircraft.

It is likely that the performance benefit is restricted by the method of displaying glide slope error (the ILS indicator), since pilot comments show a clear and progressive improvement from basic aircraft to DLC and then to DLC + MB.

7.2 Flare performance

The quality of the visual display, and other elusive factors, make the simulation of flare and touchdown a matter of contention. In no ground based simulator can pilots perform the flare manoeuvre as well as they do in flight. With sufficient time on the simulator, techniques can be learned to achieve better performance, and it is certainly true that not all the pilots taking part in this investigation had mastered these techniques.

Nevertheless, the primary purpose, to compare performance of different systems, was achieved, and the results as histograms of sink rate at touchdown, are seen on figures 17 and 18. For both the forward and aft c.g. cases, the DLC + MB is clearly superior. This conclusion is substantiated by the 'probability of exceeding a given sinkrate' curves (figures 19 and 20). At the aft c.g., the DLC alone gives more improvement than MB alone. It is comforting to see also that the basic aircraft at forward c.g. is better than the basic aircraft at aft c.g. since this result is in line with pilot's comments. A further conclusion that emerges from figures 19 and 20 is that the DLC + MB improves the aft c.g. case to at least the same standard as the forward c.g. with DLC + MB. A system which eliminates performance differences due to c.g. position is very desirable.

7.3 Pilot Comments

To reproduce all the pilot comment sheets would be unprofitable. Relevant comments on the various configurations have been selected, and are presented in appendix 3. It is not too much of an oversimplification to say that they all preferred the DLC + MB system. They were less unanimous as to whether MB alone was preferable to DLC alone. Those pilots who praised DLC liked the improved control of vertical speed that it gave (on the VSI); two pilots who criticised it said that the aircraft was more sluggish in pitch. These comments simply reflect the fact that pilot opinion is based both on flight path and attitude control. DLC will improve only the former, and MB will improve only the latter. The combination of DLC and MB helps both these aspects.

Either DLC or MB gives some improvement to the basic aircraft handling - more noticeable at the aft c.g. than the forward c.g., as might be expected.

Some criticisms were made of the simulation in general. The lateral control task was thought to be rather too difficult. The need to fly one handed when cutting power in the flare was mentioned. The visual display was inadequate for the landing task. Nevertheless, if the flare results are used with caution, the simulation was adequate for the purpose of the investigation.

7.4 General Remarks

The results show that the most complex system, in which both the spoilers and elevators are driven by transient control signals, gives the best performance. It should also be noted that if these systems were applied to a larger aircraft than a VC 10, the successful design of a pure DLC system becomes more difficult, because the short period mode gets longer, and droop in the normal acceleration response gets worse. In contrast, the DLC + MB system can be tuned to get a much more favourable response. On the debit side, the DLC + MB system requires signals to the elevator as well as the spoiler which do not reflect back on stick position, so that the current transport aircraft autopilots are unsuited to this need. It is also likely that a fixed gain system (i.e. independent of speed or configuration) would be acceptable for low speed flight.

If electrical signalling to both a DLC device and to the elevator is available, the obvious question is "could not the autopilot modes be improved?". As reference 6 points out, the full benefit of DLC is more likely to be realised through the autopilot than through the pilot. The reasons are twofold - first, display of information to the pilot does not then, constitute a performance limitation.

Secondly, there is more flexibility in choice of control loops which may be closed. For example, an autopilot could happily function varying lift without pitch attitude changes, whereas considerable pilot adaption would be necessary to such a radical change of control.

Finally, the need for flight validation is very apparent. The ground based simulator can only represent certain aspects of the overall situation, and in some areas, this representation is a grey shadow of reality. It is clear that performance in the flare is such an area. The influence on pilot opinion of severe atmospheric turbulence could be powerful, in a system with direct lift inputs: again flight experience is much more meaningful than simulator trials.

8. CONCLUSIONS

8.1 The practical aspects of a DLC system suitable for a VC 10 or other large aircraft have been studied on a fixed base simulator. The system was based on the use of symmetrical wing spoilers to provide incremental lift.

8.2 Although some improvement in accuracy of control was found both on the glide slope and in the landing flare with DLC, the degree of improvement was not as marked as theory might suggest. Practical factors limit the extent to which this form of DLC may be used. These are:

i) the optimum elevator spoiler gearing is dependent on c.g. position,

ii) the DLC must be d.c. blocked, because of authority limits,

iii) the system is sensitive to the short period dynamics of the aircraft, and to the spoiler actuator dynamics.

8.3 A similar degree of improvement can be obtained by the use of the elevator alone, if an additional d.c. blocked elevator signal is added to the basic control (Manoeuvre Boost).

8.4 The combination of DLC and MB provides a substantial improvement to the longitudinal handling qualities. The MB inputs allow the practical limitations of DLC to be overcome, and it is relatively easy to optimise the longitudinal handling qualities over a large range short period dynamics. Thus this system would appear to be more suitable for very large aircraft than DLC alone.

8.5 A limit to the extent to which piloted control accuracy can be improved lies in the manner in which errors are displayed to the pilot. Unless suitable display systems are developed to take advantage of control improvements of this type, DLC is likely to be more usefully employed as a means of improving performance under automatic control. Not only are suitable feedback signals available in the autopilot, but also there is no need to provide 'conventional' control response, to satisfy the pilot.

8.6 The fixed base simulator results relating to the landing flare can at best be claimed to show a trend. As is usual in tests of this type, rates of sink at touchdown are much higher than those measured in flight. It is essential also to validate the results obtained in the simulator under turbulent conditions, to see if any overcontrolling tendency might appear. Thus the case for in-flight trials of DLC is very strong.

8.7 Certain recommendations emerge relating to flight trials.

i) To allow a DLC + MB system to be evaluated in flight, it must be possible to inject electrical signals both to the spoilers and to the elevators (the latter via either an expanding link or series actuator).

ii) The effect of system changes can easily be masked by other random factors. If performance measures are required to supplement pilot opinion, then close attention must be given to the method of measurement, recording, and analysis.

iii) Flight time is precious. It would seem to be essential that a ground based simulator programme is run concurrently with any flight test programme, to guide the flight programme in the most rewarding direction.

8.8 The preferred system, DLC + MB, is not likely to be sensitive to aircraft configuration or speed changes. No adverse effects on speed stability, stalling, or overshooting were apparent during the investigation, but these questions were looked at in a superficially way during the course of the main investigation. The performance trade-off which DLC gives, as distinct from the handling qualities improvement, is still an open question.

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Table 1

FWD c.g.

BASIC A/C

	T/D	ANG.ERROR100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
PILOT	SINK RATE	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM
A	4.2	1.56	1.2	0.458	-0.625	0.527	0.766	0.322	0.26
	4.5	-0.57	2.0	0.401	0.855	0.572	0.855	0.213	0.152
	4.7	0.13	1.75	-0.239	-0.163	0.239	0.755	0.029	0.738
B	11.5	2.33	0.35	-0.106	-0.489	0.88	0.653	0.946	0.261
	8.7	2.73	-1.55	0.404	-0.932	0.768	0.932	0.985	0.184
	8.8	1.8	0.55	0.056	-0.372	0.481	0.437	0.387	0.111
C	6.0	-0.63	0.85	-0.362	-0.153	0.362	0.482	0.017	0.255
	2.7	-1.47	0.55	0.215	-0.323	0.441	0.446	0.198	0.142
	7.0	-2.29	0.61	-1.096	-0.213	1.096	0.277	0.205	0.058
E	12.0	-0.33	2.0	0.298	0.672	0.318	0.672	0.021	0.33
	9.0	-1.33	2.45	-0.404	0.779	0.404	0.779	0.09	0.397
F	15.0	-0.13	0.838	-0.286	0.022	0.286	0.339	0.077	0.151
	9.0	-0.968	2.306	-0.085	0.317	0.314	0.338	0.142	0.084
	10.0	-1.668	-0.628	-0.674	0.042	0.674	0.3	0.153	0.126
	5.0	0.06	0.7	-0.04	-0.005	0.178	0.551	0.035	0.355
G	6.0	0.03	1.45	0.338	0.978	0.338	0.978	0.013	0.095
	12.5	-0.59	1.05	-0.053	0.733	0.097	0.733	0.019	0.144
	6.0	-0.8	1.35	-0.4	0.607	0.4	0.722	0.051	0.548
H	8.0	0.73	1.1	2.173	0.086	2.173	0.181	0.426	0.069
	11.0	-0.03	1.95	-0.845	0.277	0.845	0.36	0.077	0.182
	6.0	-1.03	-1.0	-1.075	0.047	1.075	0.342	0.084	0.185

Table 2

FWD c.g.

D.L.C.

PILOT	T/D	ANG.ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
	SINK RATE	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	4.6	0.6	1.15	0.059	-0.712	0.208	0.828	0.077	0.492
	2.4	-0.53	0.85	-0.32	0.131	0.32	0.606	0.01	0.411
	11.5	1.56	1.25	0.564	0.224	0.763	0.424	0.474	0.231
B	7.5	0.4	0.35	0.375	-0.383	0.437	0.422	0.092	0.064
	5.5	1.33	-0.4	0.181	-0.681	0.335	0.681	0.185	0.127
	3.5	-1.47	1.15	0.288	-0.428	0.56	0.617	0.307	0.257
C	7.4	-1.23	-0.25	-0.177	0.018	0.348	0.155	0.169	0.035
	8.5	-1.83	-0.25	0.025	-0.677	0.625	0.671	0.508	0.041
E	6.2	-0.4	1.95	0.118	0.569	0.189	0.614	0.037	0.366
	12.0	0	1.95	-0.09	0.091	0.105	0.476	0.01	0.41
F	6.2	-	-	-0.146	0.168	0.175	0.185	0.027	0.024
	5.6	-	-	0.261	0.331	0.334	0.548	0.075	0.391
G	0	-1.28	0.51	-0.922	0.425	0.922	0.706	0.029	0.459
	8.5	-0.73	0.35	-0.227	0.154	0.229	0.387	0.027	0.158
	8.5	-1.0	1.75	-0.71	-0.111	0.71	0.678	0.02	0.689
H	9.5	-0.67	0.75	-0.077	-0.056	0.166	0.127	0.034	0.027
	7.2	-0.75	0.75	-0.159	0.003	0.158	0.176	0.017	0.052

Table 3

FWD c.g.

M.B.

PILOT	T/D	ANG. ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
	SINK RATE	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
B	11.9	-0.67	0.7	0.124	-0.176	0.212	0.407	0.058	0.185
	9.6	-0.87	0.8	0.041	-0.023	0.299	0.189	0.11	0.065
	7.8	0.6	-1.05	-0.174	-0.481	0.244	0.481	0.073	0.035
C	10.6	-1.13	1.45	-1.351	-0.48	1.351	0.831	0.119	0.73
	12.0	-2.49	-0.45	-1.68	-0.269	1.68	0.269	0.059	0.015
	5.0	-1.28	0.71	0.377	0.352	0.377	0.461	0.054	0.218
H	9.0	-1.8	0.95	0.399	-0.078	0.642	0.51	0.347	0.358
	15.0	-2.2	0.6	-0.395	0.132	0.413	0.557	0.228	0.411
	6.0	-1.93	1.6	-0.586	-0.03	-0.586	0.402	0.152	0.274

D.L.C. + M.B.

PILOT	T/D	ANG. ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
	SINK RATE	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	5.2	-0.07	1.75	-0.178	1.04	0.178	1.04	0.005	0.045
	4.8	-0.47	1.8	0.152	1.776	0.258	1.776	0.062	0.06
	1.7	-1.4	-0.85	-0.415	-0.4	0.415	0.405	0.074	0.198
C	8.9	-0.67	1.4	0.312	-0.781	0.372	0.932	0.057	0.385
	6.0	-2.6	-0.1	-1.172	-0.369	1.172	-0.393	0.3	0.077
	9.5	-2.13	0.85	-0.627	-0.11	0.627	0.257	0.158	0.117
E	5.8	-0.33	2.05	-0.144	1.099	0.177	1.161	0.031	0.712
	9.4	-0.77	0.15	-0.221	0.246	0.224	0.311	0.039	0.062
F	8.5	-	-	-0.05	-0.283	0.998	0.498	2.061	0.25
	4.0	-	-	0.007	-0.193	0.539	0.277	0.555	0.065
	6.5	-	-	-0.277	0.371	0.357	0.564	0.09	0.249
	5.6	0.5	-0.05	0.185	0.164	0.185	0.267	0.015	0.116
G	7.5	-0.93	1.5	-0.277	1.319	0.277	1.319	0.028	0.027
	6.7	-0.65	0.56	-0.116	-0.146	0.143	0.406	0.029	0.206
	6.0	-0.37	1.15	0.038	0.203	0.105	0.528	0.015	0.362
H	9.0	-1.1	1.8	-0.629	0.051	0.629	0.277	0.015	0.177
	8.0	-0.67	0.95	0.188	-0.02	0.277	0.223	0.066	0.089
	5.0	-1.9	0.6	-0.484	-0.582	0.487	0.953	0.236	0.89

Table 4

AFT c.g.

BASIC A/C

PILOT	T/D SINK RATE	ANG.ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
		ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	6.5	-1.03	1.7	-0.023	0.01	0.518	0.522	0.063	0.423
	4.5	-1.27	0.15	-0.516	-0.09	0.516	0.353	0.049	0.148
	5.5	-0.23	1.4	-0.034	0.339	0.209	0.47	0.051	0.226
B	10.4	0.8	2.25	0.158	0.481	0.205	0.489	0.072	0.331
	8.5	0.03	1.95	0.219	0.378	0.219	0.454	0.011	0.231
	11.4	-0.73	1.25	0.313	0.335	0.447	0.559	0.27	0.337
D	11.0	-0.03	0.95	0.728	0.92	0.729	0.92	0.197	0.016
	14.5	-0.13	1.5	0.038	0.569	0.282	0.569	0.107	0.247
	6.0	0.2	1.45	0.187	0.42	0.274	0.51	0.057	0.237
E	11.5	-0.43	0.75	-0.357	0.344	0.357	0.344	0.052	0.068
F	11.6	-0.4	2.2	-0.7	0.618	0.7	0.622	0.152	0.358
	9.0	-0.83	0.25	-0.273	0.119	0.277	0.312	0.033	0.138
	9.3	-0.23	1.3	-0.3	0.102	0.302	0.378	0.042	0.199
	6.3	0.6	0.15	0.004	0.058	0.259	0.161	0.088	0.035
	7.2	0.1	0.25	0.518	0.214	0.518	0.266	0.057	0.084
	16.3	-	-	-0.415	0.584	0.427	0.748	0.238	0.618
	15.7	-	-	0.097	0.991	0.191	0.945	0.057	0.281
	16.3	-	-	0.268	0.247	0.655	0.424	0.452	0.286
G	9.4	-1.1	0.45	0.108	0.337	0.244	0.357	0.095	0.08
	5.5	-0.1	1.35	0.418	0.211	0.46	0.296	0.079	0.108
	3.0	-0.67	1.3	-0.172	0.279	0.173	0.285	0.034	0.124
H	16.0	2.1	4.9	-0.349	0.486	0.645	0.941	0.394	2.004
	3.5	-1.7	-1.45	-0.174	0.113	0.369	0.51	0.23	0.393
	17.0	-2.6	-0.75	-0.62	0.613	0.62	0.731	0.263	0.346
I	10.0	-	-	1.358	0.316	1.426	0.96	0.479	1.187
	7.5	-	-	-0.575	-0.198	0.691	0.507	0.61	0.324
J	4.7	-1.97	3.45	-0.824	0.426	0.824	0.944	0.115	1.541
	9.9	0.33	3.9	-0.213	0.555	0.728	0.599	0.613	0.945
	12.0	0.33	3.8	-0.86	0.385	0.871	0.579	0.211	0.854

AFT. c.g.

D.L.C.

PILOT	T/D SINK RATE	ANG. ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
		ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	2.0	-1.57	0.75	-0.597	1.092	0.597	1.092	0.143	0.086
	3.0	-0.93	0.35	-0.347	-0.389	0.347	0.495	0.028	0.143
	0	0.4	-0.05	0.126	-0.068	0.165	0.251	0.03	0.076
B	6.7	-0.13	1.1	-0.331	0.057	0.369	0.34	0.067	0.168
	6.0	-1.27	0.7	-0.261	0.252	0.386	0.405	0.176	0.161
	15.4	-0.3	1.65	0.124	0.168	0.197	0.399	0.044	0.248
D	7.6	0.33	1.7	0.069	0.256	0.364	0.46	0.151	0.33
	6.6	-0.13	1.35	-0.092	0.263	0.165	0.375	0.026	0.181
	6.6	-0.3	1.25	0.161	0.245	0.18	0.379	0.016	0.196
E	4.3	-0.67	0.45	-0.082	0.391	0.369	0.393	0.163	0.083
	8.0	-0.43	1.65	0.046	0.186	0.15	0.7	0.034	0.681
	8.5	-0.83	0.7	-0.099	0.576	0.188	0.576	0.055	0.101
F	4.2	-0.57	0.4	0.602	-0.13	0.64	0.655	0.118	0.531
	6.6	-	-	-0.223	0.848	0.227	0.848	0.007	0.462
	5.1	-	-	0.112	-0.065	0.168	0.694	0.021	0.666
G	4.0	-1.01	1.36	0.141	0.447	0.327	0.447	0.119	0.061
	2.0	-0.47	0.05	0.187	0.913	0.304	0.913	0.074	0.201
	2.0	-0.83	1.6	0.076	0.594	0.267	0.595	0.096	0.207
H	5.2	-2.63	2.05	-0.797	0.085	0.797	0.441	0.26	0.391
	4.7	-1.7	0.15	-0.355	0.058	0.394	0.398	0.125	0.275
	9.0	-0.23	0.15	-0.174	-0.116	0.177	0.354	0.014	0.182
I	5.5	-	-	-1.282	-0.606	1.282	0.695	0.441	0.387
	2.5	-	-	-0.973	-0.461	1.075	1.062	1.301	1.618
J	9.9	-1.3	2.15	-0.693	0.122	0.693	0.434	0.076	0.407
	11.7	-0.34	1.77	-0.006	0.262	0.078	0.357	0.01	0.18
	8.2	-1.77	2.86	-0.415	0.355	0.522	0.596	0.292	0.782

Table 6

AFT c.g.

D.L.C. + M.B.

PILOT	T/D SINK RATE	ANG. ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
		ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	4.2	-0.5	1.35	-0.191	0.083	0.203	0.267	0.021	0.159
	4.2	-0.87	0.4	-0.4	-0.935	0.4	0.961	0.01	0.152
	3.9	-0.77	1.0	-0.178	-0.373	0.181	0.888	0.031	0.791
B	9.1	-1.3	1.65	-0.061	0.008	0.228	0.383	0.1	0.228
	7.0	-0.87	1.25	0.135	-0.014	0.307	0.352	0.093	0.223
	8.0	-1.82	0.71	-0.15	0.515	0.342	0.515	0.23	0.087
D	5.7	-0.67	1.1	-0.305	0.253	0.389	0.472	0.163	0.234
	4.6	-0.53	0.85	-0.355	-0.208	0.355	0.475	0.038	0.22
	5.6	-0.23	0.95	-0.102	0.27	0.109	0.292	0.005	0.047
E	5.0	-1.2	0.05	-0.167	0.593	0.328	0.672	0.16	0.277
	2.0	-1.6	0.35	-0.589	0.82	0.589	0.82	0.085	0.075
	0	-0.47	0.85	-0.54	0.51	0.54	0.649	0.017	0.279
F	3.7	0.6	-1.2	0.241	0.217	0.323	0.411	0.11	0.184
	6.3	-0.23	0.95	0.33	0.081	0.453	0.203	0.226	0.076
	7.3	-0.33	1.0	-0.322	0.219	0.322	0.27	0.011	0.066
	2.1	-0.03	1.1	0.125	0.47	0.256	0.478	0.073	0.196
	3.9	-0.5	1.0	0.463	0.14	0.517	0.481	0.109	0.273
	4.8	-0.6	1.8	-0.146	0.448	0.18	0.58	0.04	0.278
	3.5	-	-	0.221	0.342	0.227	0.409	0.018	0.212
	4.7	-	-	-0.03	0.066	0.169	0.38	0.035	0.279
G	6.0	-1.02	0.36	-0.177	0.186	0.177	0.42	0.044	0.207
	1.0	-1.0	1.95	0.305	-0.603	0.762	0.927	2.056	0.571
	4.2	-0.33	0.35	0.194	0.387	0.218	0.387	0.021	0.004
H	4.5	-1.7	-0.35	-0.308	-0.506	0.312	0.515	0.131	0.149
	8.5	-2.6	0.45	-0.687	-0.59	0.687	0.622	0.237	0.14
	8.7	-1.3	-0.2	-0.081	-0.121	0.182	0.32	0.075	0.133
I	3.5	-	-	-0.51	0.026	0.583	0.559	0.905	0.379
	4.5	-	-	-1.225	0.079	1.225	0.56	0.307	0.445
	1.8	-	-	-0.661	0.527	0.674	0.586	0.561	0.153

Table 7

AFT c.g.

M.B.

PILOT	T/D SINK RATE	ANG. ERROR 100'		MEAN ERROR		MEAN MODULUS		STAND DEVIATION	
		ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.	ELEV.	AZIM.
A	7.0	-0.5	-0.25	-0.082	-1.048	0.109	1.048	0.01	0.061
	7.0	0.6	1.55	0.629	0.28	0.629	0.764	0.015	0.658
	5.5	-0.6	0.30	-0.279	0.071	0.279	0.139	0.013	0.022
B	2.8	-0.1	0.75	0.409	0.237	0.417	0.448	0.033	0.206
	4.7	-0.71	0.3	0.058	-0.37	0.283	0.406	0.101	0.071
	6.5	-0.4	1.9	0.174	0.464	0.215	0.544	0.047	0.363
D	10.7	-0.87	1.4	-0.495	0.396	0.495	0.511	0.025	0.281
	6.8	-0.8	1.65	-0.101	0.136	0.188	0.399	0.055	0.272
	4.8	0.1	1.75	0.315	0.406	0.315	0.477	0.008	0.307
F	6.4	-0.37	-0.05	0.242	0.242	0.29	0.475	0.038	0.411
	7.5	1.13	-0.85	-0.013	0.074	0.444	0.603	0.279	0.598
	4.1	-0.87	1.65	0	0.661	0.303	0.661	0.129	0.123
	7.0	0.03	1.05	-0.394	0.305	0.394	0.723	0.028	0.587
	5.3	-1.6	-0.05	-0.638	0.127	0.649	0.321	0.175	0.139
	8.0	-1.1	0.4	-0.287	-0.29	0.387	0.393	0.137	0.112
G	2.2	-0.73	1.6	0.261	0.625	0.49	0.638	0.211	0.131
	0	-0.73	1.35	-0.068	0.991	0.233	0.991	0.08	0.054
	2.2	-0.77	0.45	-0.054	0.3	0.147	0.3	0.032	0.025
H	14.0	-2.27	-0.25	-0.506	-0.325	0.506	0.54	0.224	0.265
	12.0	-2.07	1.75	-0.379	0.007	0.379	0.49	0.155	0.355
	1.8	-2.6	0.75	-0.75	-0.263	0.75	0.534	0.284	0.321
J	16.6	1.26	3.1	1.386	-0.392	1.386	0.678	0.029	0.544
	16.8	0.03	4.85	0.736	1.341	0.739	1.354	0.089	1.746
	4.0	-1.53	2.75	-0.541	0.226	0.541	0.357	0.054	0.457

Aerodynamic data used in simulation

1. Aircraft Conditions

Weight 212,000 lbs.

Flaps: selectable 45°, 30°, 20°, 0

Undercarriage down, slats out.

Datum configuration: 138.5 knots, flaps 45°

M. of I. in pitch, I_y 200×10^6 lb ft^2

M. of I. in roll, I_x 60×10^6 lb ft^2

M. of I. in yaw, I_z 238×10^6 lb ft^2

I_{xz} 11.3 lb ft^2

Wing area 2806 ft^2

Mean chord $\bar{c}$ 20.0 ft

Tail arm l_T 61.7 ft

Span b 140 ft

2. Longitudinal aerodynamics

C_L - see fig. 3

C_M - see fig. 4

C_D - see fig. 5

$m_q = -0.453$ $\qquad$ $z_w = -2.52$

$m_{\dot{w}} = -0.064$ $\qquad$ $z_\eta = -0.171$

$m_\eta = -0.171$ $\qquad$ $z_{\delta_s} = -0.172$

$$\text{Thrust} \quad T = \frac{1}{1 + S} \cdot 80{,}000 \, \frac{\delta_T}{\delta_{T_{Max}}} \ \text{lbs}$$

Spoiler characteristics (for DLC)

$$\Delta C_D = \left[0.0268 + 0.0165 \, C_L{}^2 \right] \frac{\delta_s}{\delta_{s_{50^\circ}}}$$

$$\Delta C_L = \left[-0.3 - 0.014 \, \alpha_B \right] \frac{\delta_s}{\delta_{s_{50^\circ}}}$$

$$\Delta C_m = \left[-0.0256 + 0.0246 \, C_L \right] \frac{\delta_s}{\delta_{s_{50^\circ}}}$$

3. Lateral derivatives

$y_v = -0.388$

$n_v = +0.108$

$n_p = -0.08$

$n_r = -0.123$

$l_v = -0.19$

$l_p = -0.398$

$l_r = +0.28$

$y_\zeta = +0.113$

$n_\zeta = -0.075$

$l_\zeta = +0.025$

$n_\xi = 0$

$l_\xi = -0.10$

Spoilers (50°)

$$C_l = -0.042$$

$$C_y = -0.024$$

$$C_n = -0.004$$

Controls

Maximum travels		
	aileron	± 15°
	elevator	-21° to +12.7°
	rudder	± 13°
	spoilers	0 - 50°

Forces

aileron/spoiler	20 lbs for full control
elevator	2.2 lbs/deg elevator
rudder pedal	120 lbs for full control

4. Ground effects

$$\Delta C_L = (.105 - .008\alpha_B)\left(1 - \frac{h}{50}\right)$$

$$\Delta C_D = (-.035 - .004\alpha)\left(1 - \frac{h}{50}\right)$$

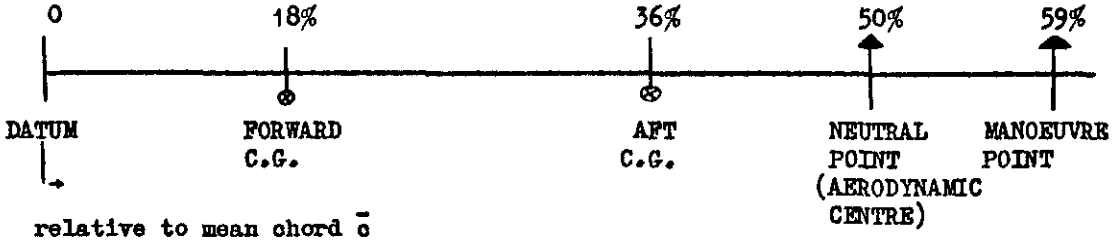
$$\Delta C_m = 0.192(C_L - .95)\left(1 - \frac{h}{50}\right)$$

for $h < 50$ ft.

$\Delta C_L = \Delta C_D = \Delta C_m = 0$ for $h > 50$ feet

During the investigation, ΔC_m was halved, following adverse pilot comments.

5. Aerodynamic and c.g. positions



		Forward c.g.	Aft c.g.
Manoeuvre Margin	H_m	+ .41	+ .23
s.p. frequency	W_n	1.07 rad/sec	0.808 rad/sec
s.p. damping	ζ_n	0.54	0.72
elevator per g	η/g	-27.5 deg	-15.5 deg
Static margin	K_n	+ .32	+ .14
$\frac{\partial C_m}{\partial \alpha}$		-1.64	- .72
m_w		- .265	- .117
Stick force/g lbs/g		60.5	34.0

6. Wind Shear and Turbulence

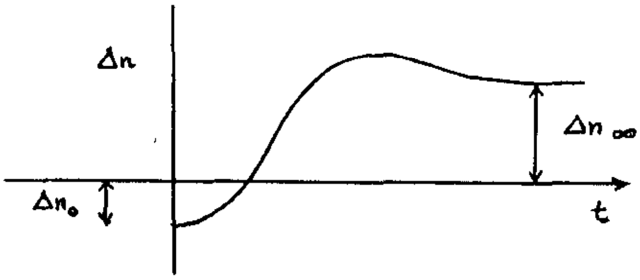
Wind shear effects were introduced as an incremental forward speed term, as a function of height. This function is shown on figure 6.

Mild turbulence was fed into all three translational equations of motion.

The conventional Dryden Spectrum was used to filter white noise. An r.m.s. level of 2ft/second was represented.

Appendix 2

The choice of gearing to the spoilers for direct lift control



For a step pitch control input η , initial g, $\Delta n_o = \rho \frac{V^2 S}{2W} \quad C_{L_\eta}$

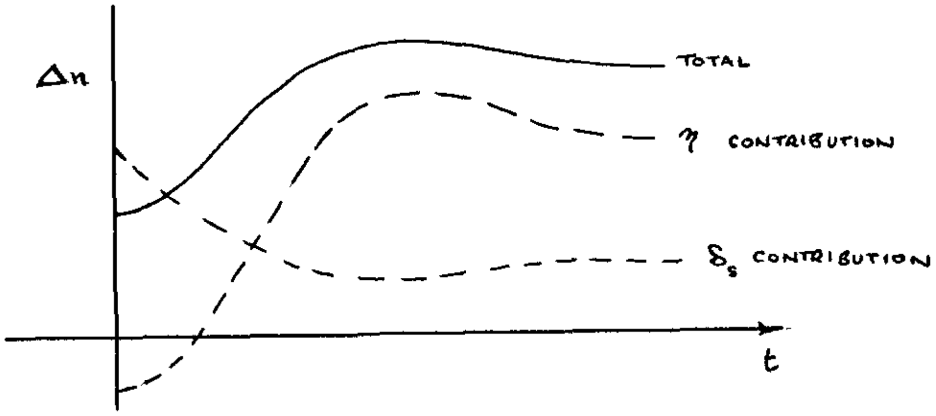
steady g, $\Delta n_\infty = -\rho \frac{V^2 S}{2W} \cdot \frac{1}{H_m} \cdot C_{L_\eta} \; K_\eta$,

where K_η = control lift moment arm $= \frac{x}{\bar{c}}$

x = distance of aerodynamic centre of control lift behind the aerodynamic centre of aircraft.

For a conventional elevator, x = tail arm, l_T.

Now assume that the normal acceleration results from the combination of two such controls, η and δ_s , which are geared together: $\delta_s = G_\eta \eta$



$$\Delta n_o = \frac{\rho V^2 S}{2W} \left(C_{L_\eta} + G\, C_{L_{\delta_s}} \right)$$

$$\Delta n_\infty = \frac{-\rho V^2 S}{2W} \cdot \frac{1}{H_m} \left[C_{L_\eta} K_\eta + G\, C_{L_{\delta_s}} K_{\delta_s} \right]$$

In the 'ideal' DLC system, $\Delta n_o = \Delta n_\infty$

$$\therefore\ C_{L_\eta} + G\, C_{L_{\delta_s}} = -\frac{1}{H_m} \left[C_{L_\eta} K_\eta + G\, C_{L_{\delta_s}} K_{\delta_s} \right]$$

$$G = \frac{-C_{L_\eta}}{C_{L_{\delta_s}}} \, \frac{\left(1 + \frac{K_\eta}{H_m}\right)}{\left(1 + \frac{K_{\delta_s}}{H_m}\right)}$$

$$\frac{C_{L_\eta}}{C_{L_{\delta_s}}} = \frac{Z_\eta}{Z_{\delta_s}} \qquad K_\eta = \frac{l_T}{\bar{c}}$$

For VC 10 spoilers, $K_{\delta_s} = -.02$. It is worth noting that K_{δ_s} is only significant when its magnitude is comparable to that of the manoeuvre margin. In other words, minor uncertainties about the position of the spoiler lift do not compromise the design of a DLC system.

Applying the VC 10 data at 138 knots, full flap, forward c.g.,

$$G = -\frac{.171}{.172} \, \frac{\left(1 + \frac{3.08}{.41}\right)}{\left(1 - \frac{.02}{.41}\right)}$$

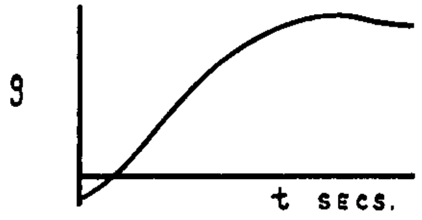
$$= \underline{\underline{-8.9}}$$

Typical Pilot Comments

c.g. Position	Configuration	Remarks	
FORWARD c.g.	Basic Aircraft	General	"not too unpleasant to fly". "quite realistic apart from lateral directional control". "lateral rocking after breaking cloud". "generally satisfactory, but noticeably slower $\dot{h}$ control via attitude" (after DLC and DLC + MB cases)
		Glide slope	"difficult to hold ILS in later stages of approach". "definitely harder work than DLC or DLC + MB" "Cooper rating 4" (after rating MB + DLC as 2, DLC as 3)
		Flare and Touchdown	"landing difficult due to TV picture limitations". "landings are more luck than judgement". "ground effects not representative". "controlled crash". "overcontrolled in flare and ballooned".
	DLC	General	"aircraft pitch response seems degraded compared to both basic and DLC + MB". "VSI is primary instrument" "better control" (cf basic aircraft) "more elevator activity needed". "controls seem more sensitive".
		Glide slope	"Glide path errors cancelled more quickly" (cf basic aircraft). "VSI helps to maintain glide slope". "Cooper rating 3" "rather sluggish response to get back onto glide path". "overcontrolling"
		Flare and Touchdown	"easier flare control".
	DLC + MB	General	"pitch control good". "MB gives instant $\dot{h}$ control as shown on VSI, very nice". "Better all round". "better control on the whole". "control improved". "much better control of speed and pitch".
		Glide slope	"easier approach than basic or DLC". "Cooper rating 2".
		Flare and Touchdown	"Much easier flare control". "fair touchdowns possible". "first reasonable landing off a poor approach". "Good landing without overcontrolling".
AFT c.g.	Basic Aircraft	General	"pitch control difficult". "difficult to trim". "ILS very sensitive late on". "aft c.g. effect very noticeable, Cooper rating 4". "oscillatory aircraft response".
		Glide slope	"ILS poor - longitudinal P.I.O". "easy to chase". "tight control difficult".
		Flare and Touchdown	"overcontrolling very easy in flare". "tendency to overflare" "porpoising over threshold" "poor flare - ballooning".
	DLC	General	"still trim troubles". "O.K. if you keep on top of it". "sluggish pitch control". "delay in pitch build up, Cooper rating 4". "smaller workload". "better h control, but basic oscillatory response still there".
		Glide slope	"no problem". "much better elevator control".
		Flare and Touchdown	"better, I think". "seems more control over flare". "flare difficult to control"
	M.B.	General	"slight longitudinal overcontrolling". "better handling than basic aircraft at aft c.g., quite nice".
		Glide slope	"Not quite so easy as DLC alone". "more skittish than DLC or DLC + MB". "slightly oversensitive". "more difficult to hold steady rate of descent".
		Flare and Touchdown	"easier flare control" (than basic aircraft)
	DLC + MB	General	"better all round". "pitch control improved". "no problem" "response in pitch is good for a big aircraft". "smaller workload". "Best combination".
		Glide slope	"better" "Cooper rating 3" "still oversensitive".
		Flare and Touchdown	"much easier than basic aircraft". "too responsive in elevation". "good control during flare".

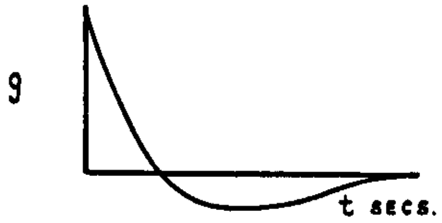
n_z RESPONSES TO STEP ELEVATOR INPUT.

FIG. 1 (a)



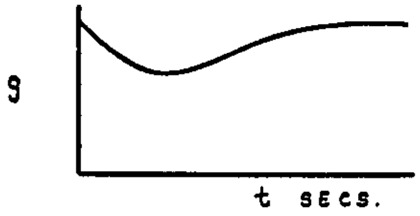
BASIC AIRCRAFT.

FIG 1 (b)



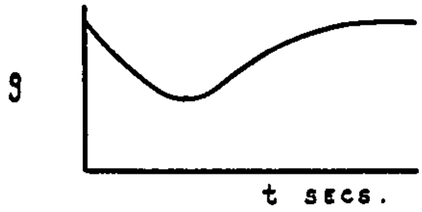
D.L.C AT AERODYNAMIC CENTRE.

FIG 1 (c)



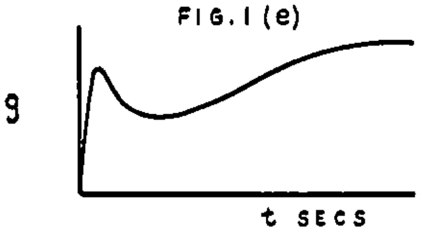
D L C. AT $H_\eta = -H_m$, OR
D.L.C. + GEARED ELEVATOR.

FIG 1 (d)



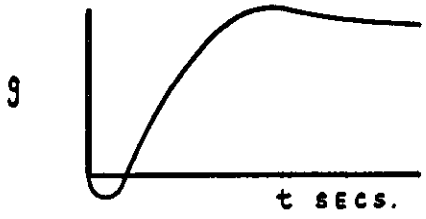
EFFECT OF d.c. BLOCKING ON (c).

FIG. 1 (e)



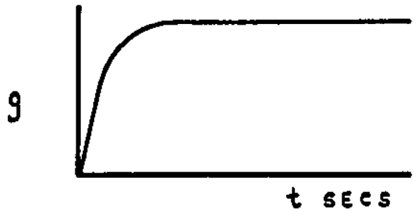
EFFECT OF POWER CONTROL LAG ON (d).

FIG. 1 (f)



MANOEUVRE BOOST

FIG. 1 (g)



COMBINED D.L.C AND MANOEUVRE BOOST.

ELEVATOR AND SPOILER CONTROL BLOCK DIAGRAM

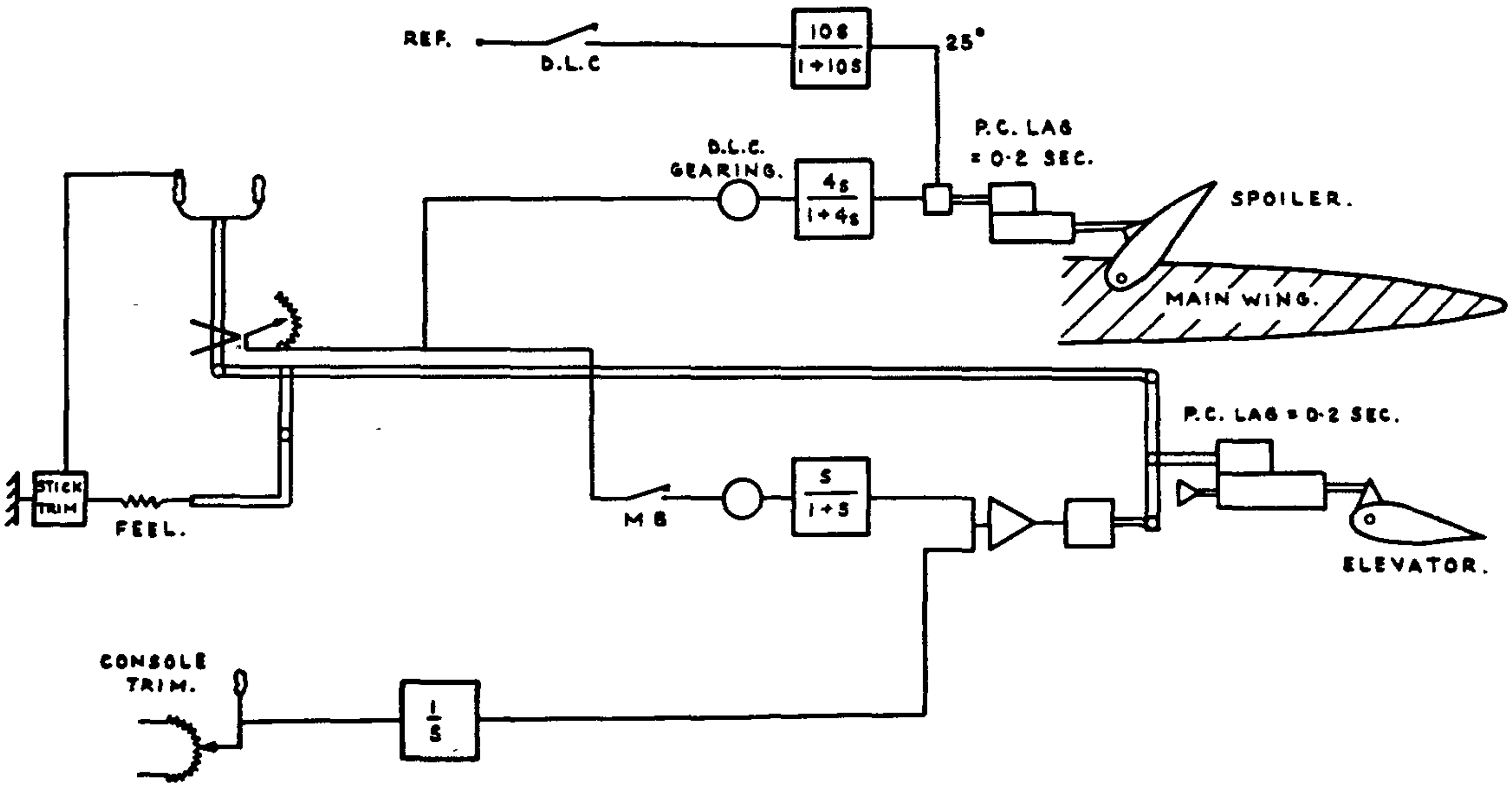


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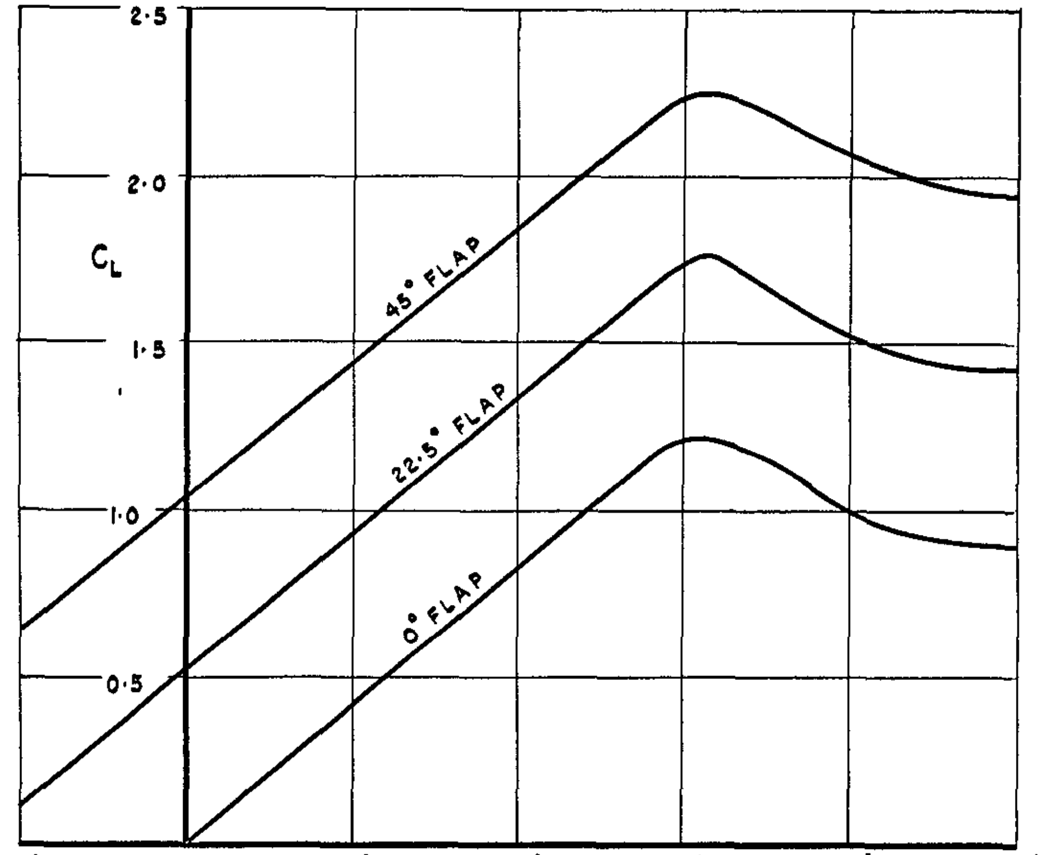
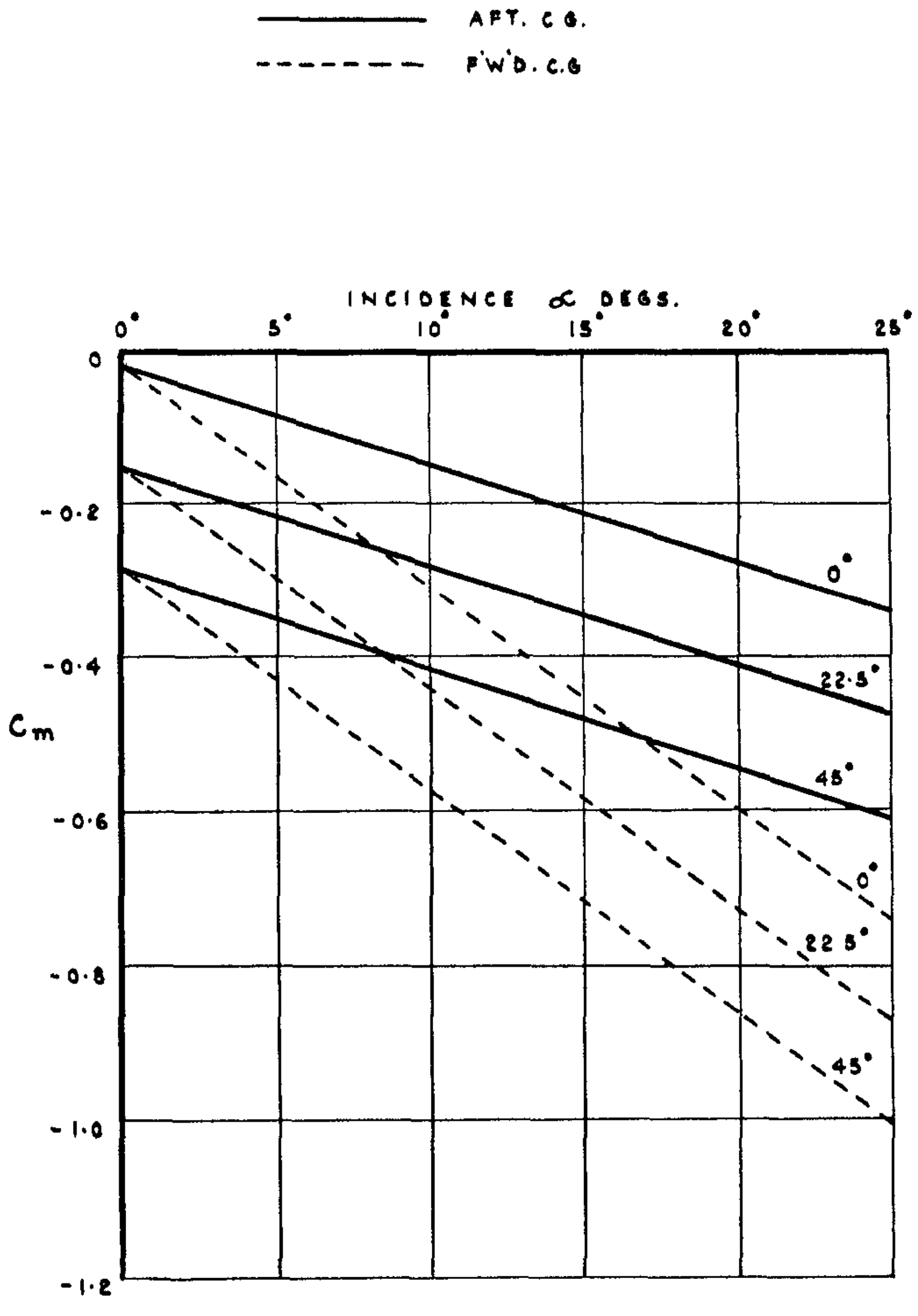
FIG 2

V.C. 10 LIFT CURVE.



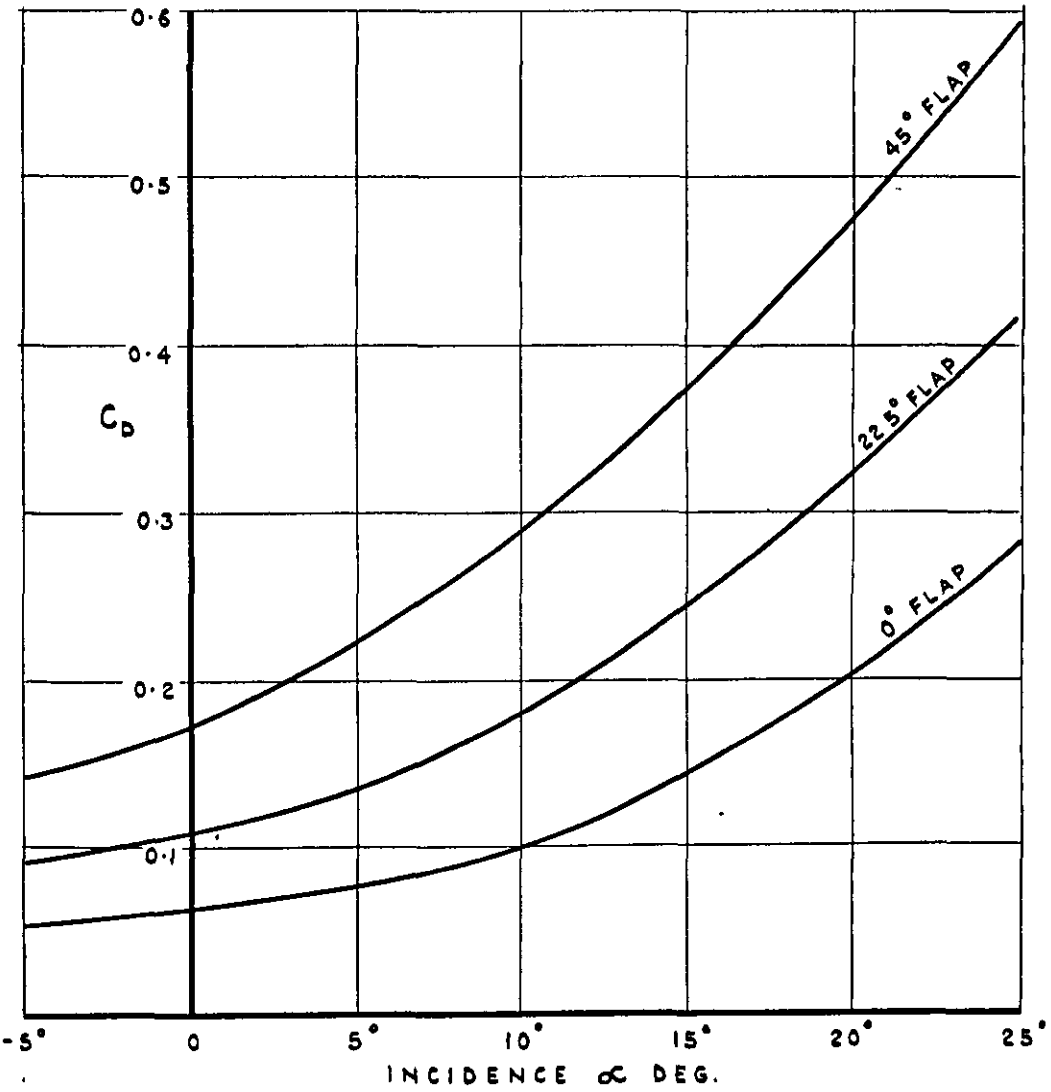
V.C. 10 C_m V α FOR 3 FLAP POSITIONS.



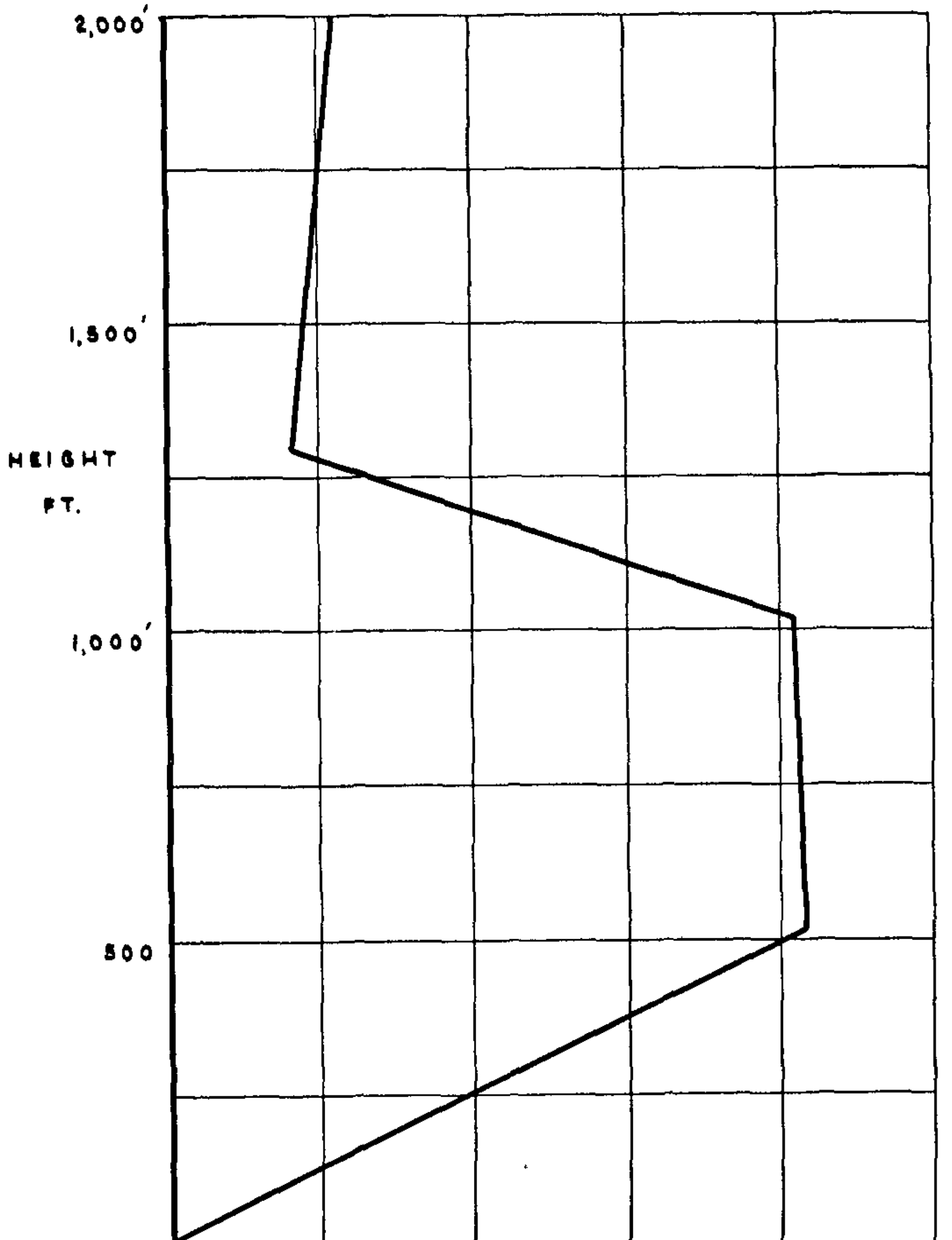
VC 10 DRAG CURVE

C_D FOR 45° FLAP BASED ON $C_D = 0.12 + 0.048\, C_L^2$

GRAPH FOR 0° FLAP BASED ON ΔC_D DUE TO FLAP = 0·05

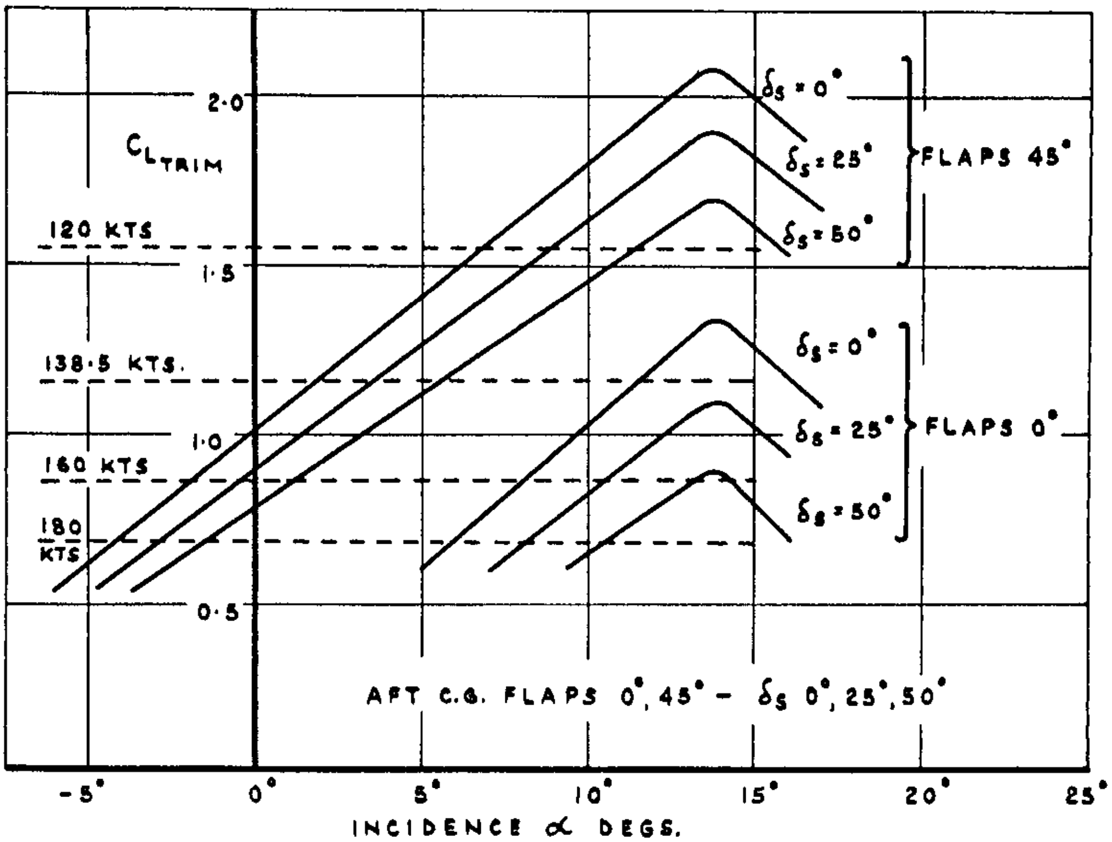


SIMULATED WIND SHEAR CURVE



V.C 10 $C_{L_{TRIM}}$ V α° CURVE SHOWING TRIM SPEEDS.

W = 212,000 LB



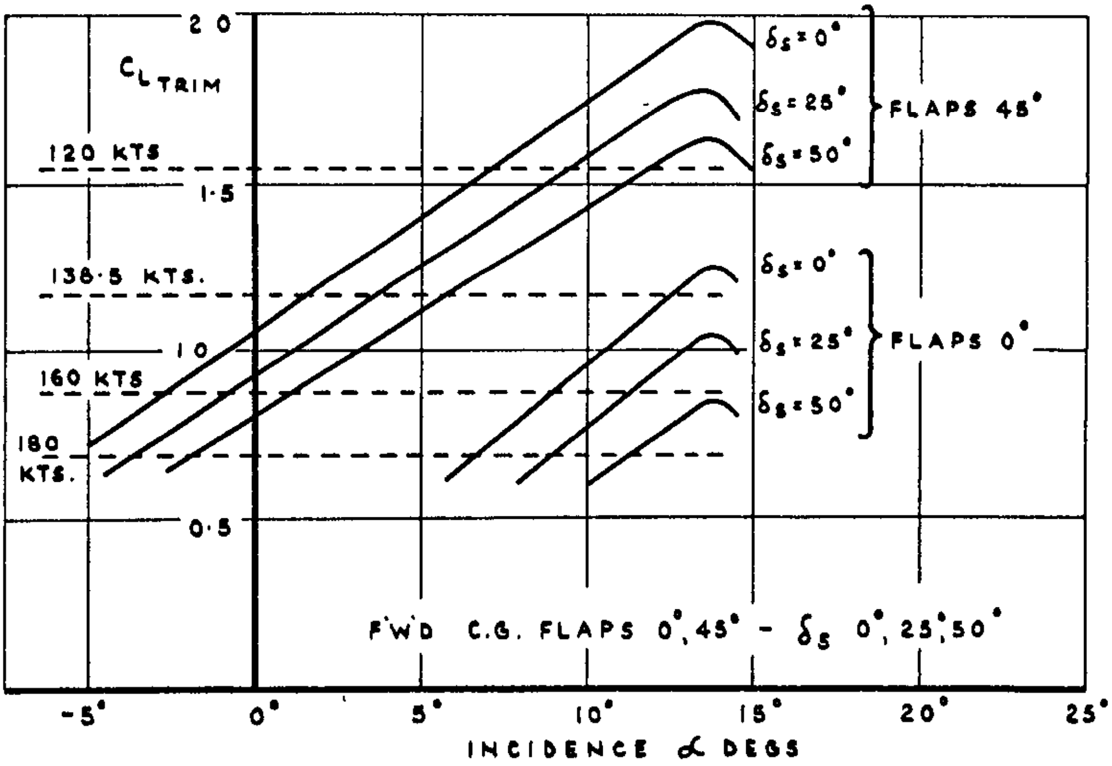


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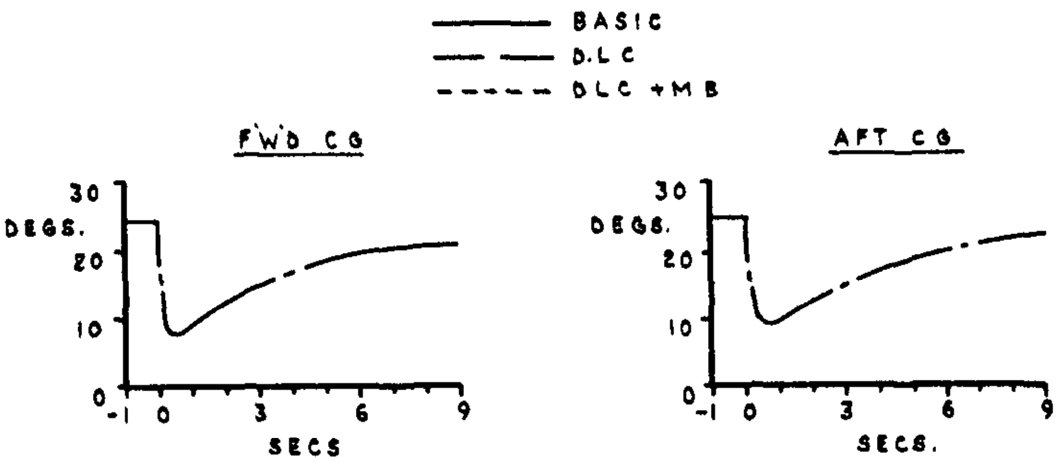
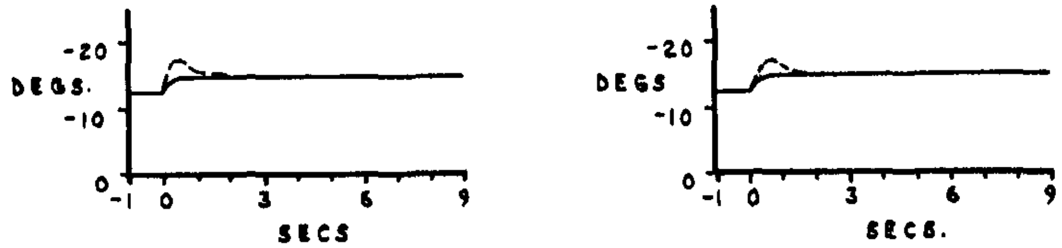
FIG. 8

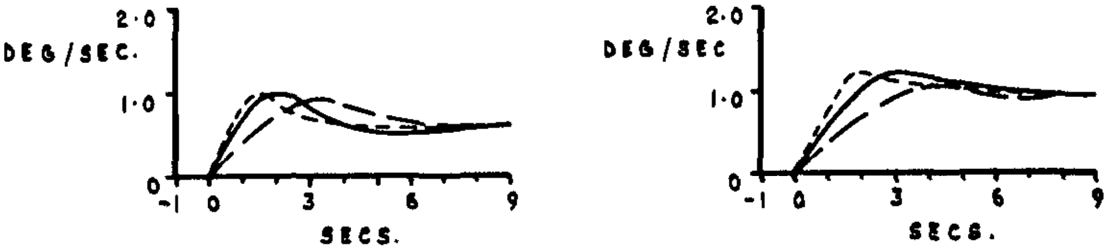
138·5 KTS. 45° FLAP.



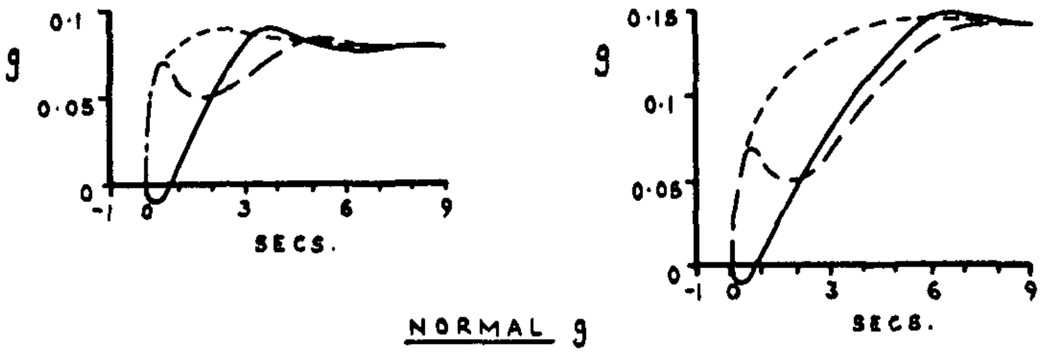
SPOILER ANGLE δ_s



ELEVATOR ANGLE η



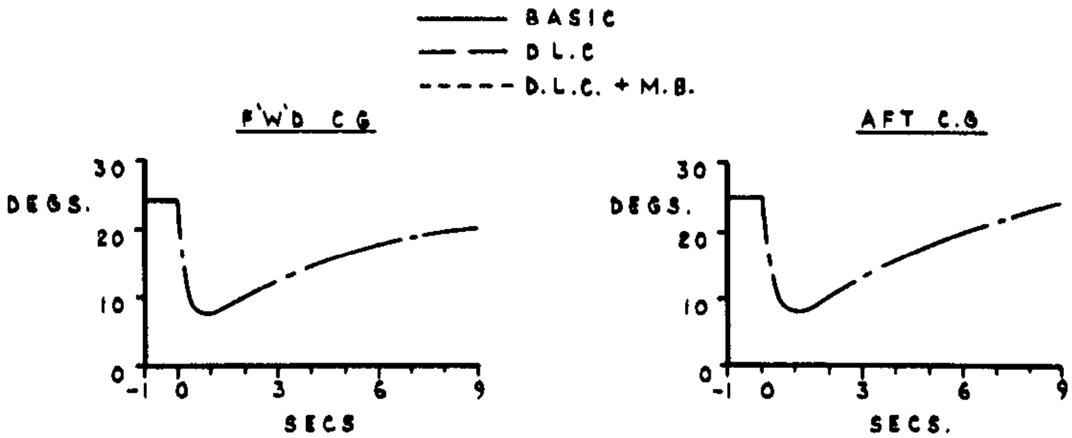
PITCH RATE q



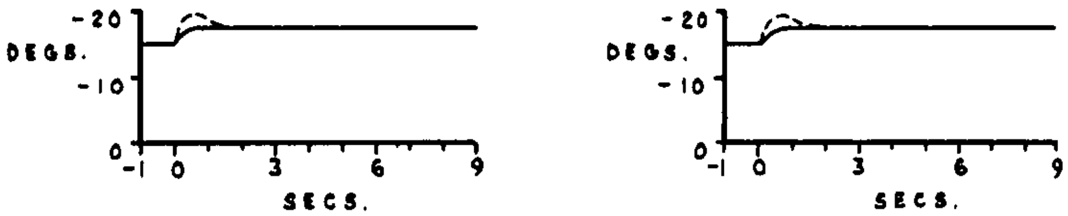
NORMAL g

FIG. 9.

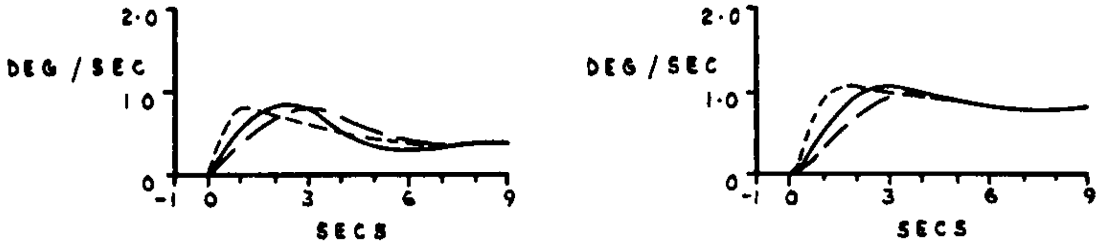
120 KTS. 45° FLAP.



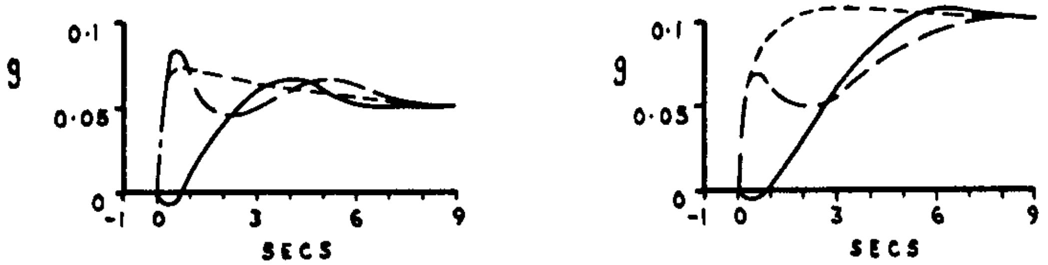
SPOILER ANGLE δ_s



ELEVATOR ANGLE η



PITCH RATE q



NORMAL g

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FIG. 10.

160 KTS. 30° FLAP.

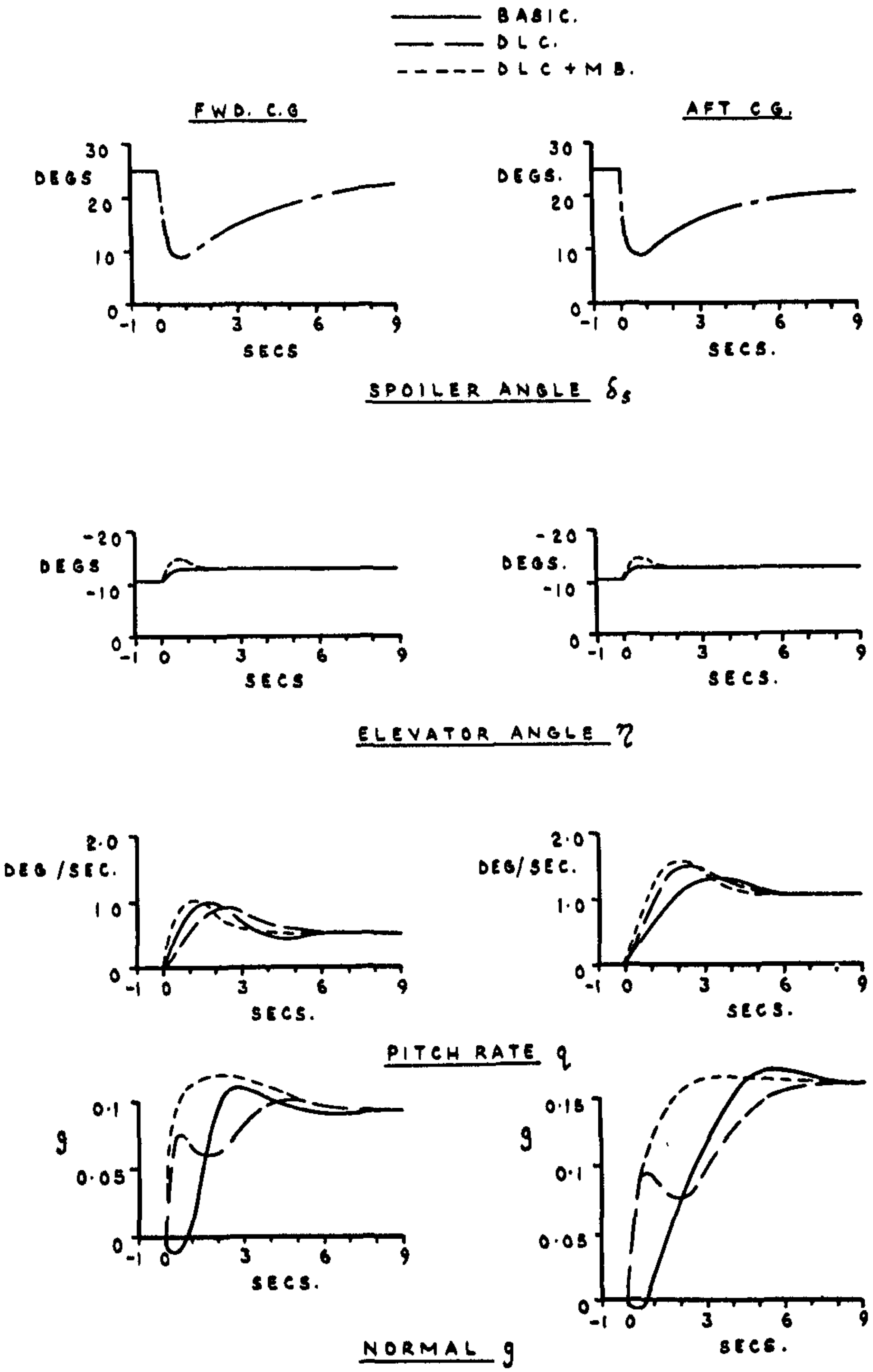
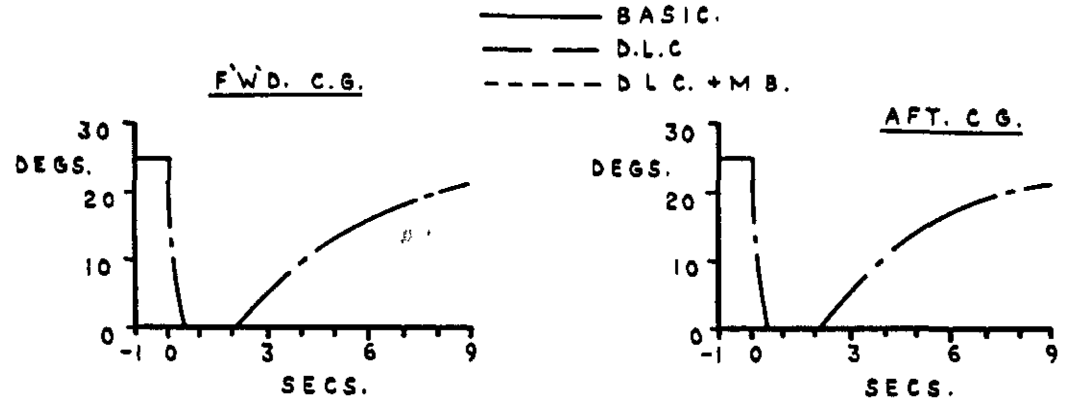
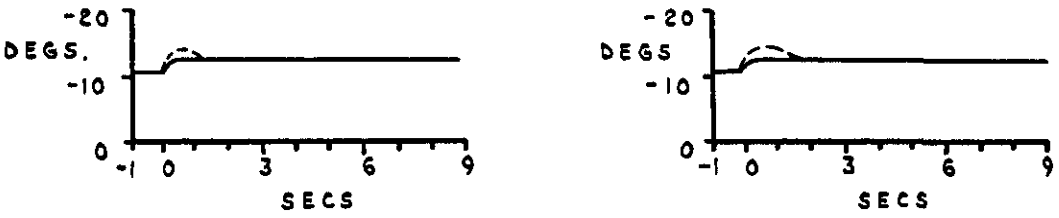


FIG. 11.

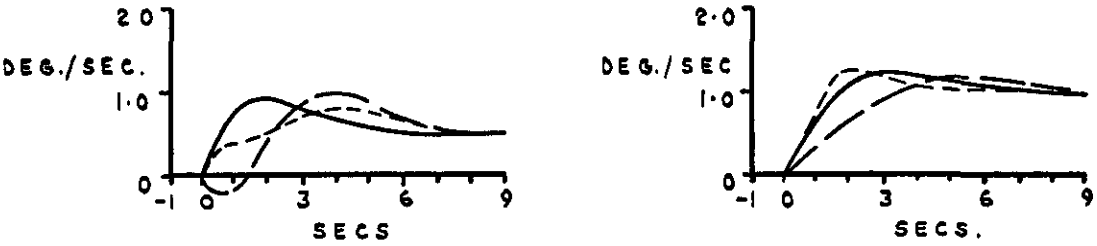
138·5 KTS. 45° FLAP.
GEARING x 2



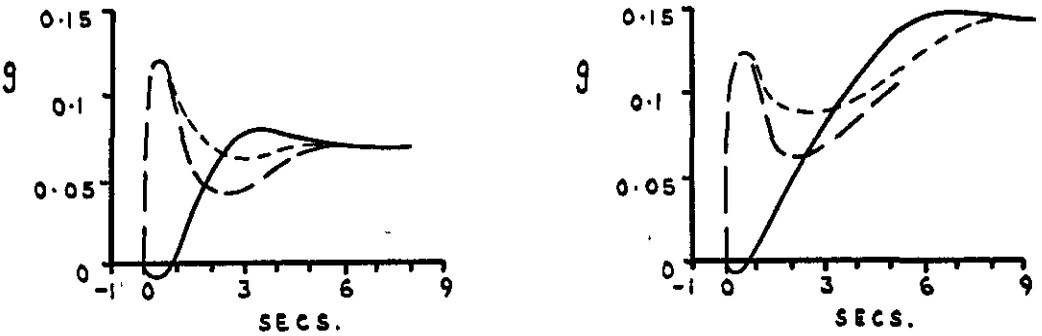
SPOILER ANGLE δ_s



ELEVATOR ANGLE η



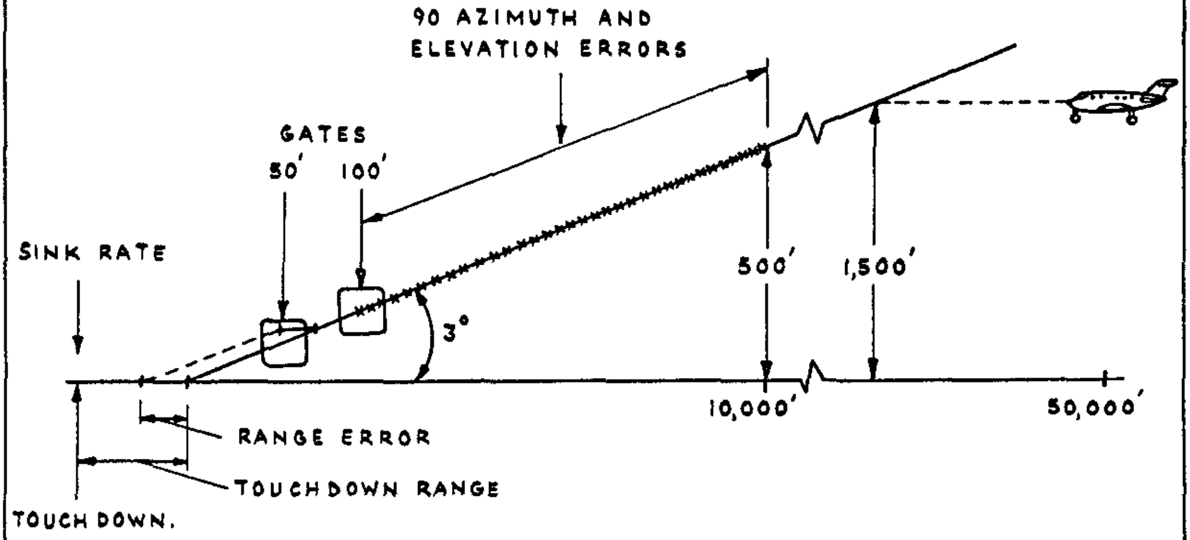
PITCH RATE q



NORMAL g.

GAF S/P 1381/69

FIG. 12.



TYPICAL COMPUTER PRINT-OUT OF RESULTS

```
RUN No. 4.                       90
T/D. RANGE = -1001·5      T/D SINK RATE = 3·514

RANGE ERROR AT 50 FT.     -1066·3
RANGE ERROR AT 100 FT.    -1068·7

ANG ERRORS AT 50 FT.      ELEV. -3·06       AZIM. 3·34
ANG. ERRORS AT 100 FT.    ELEV. -1·47       AZIM. 1·15

               MEAN ERROR    MEAN MODULUS    STANDARD DEVIATION.

ELEVATION.     0·288           0·560              0·307
AZIMUTH.      -0·428           0·617              0·257
```

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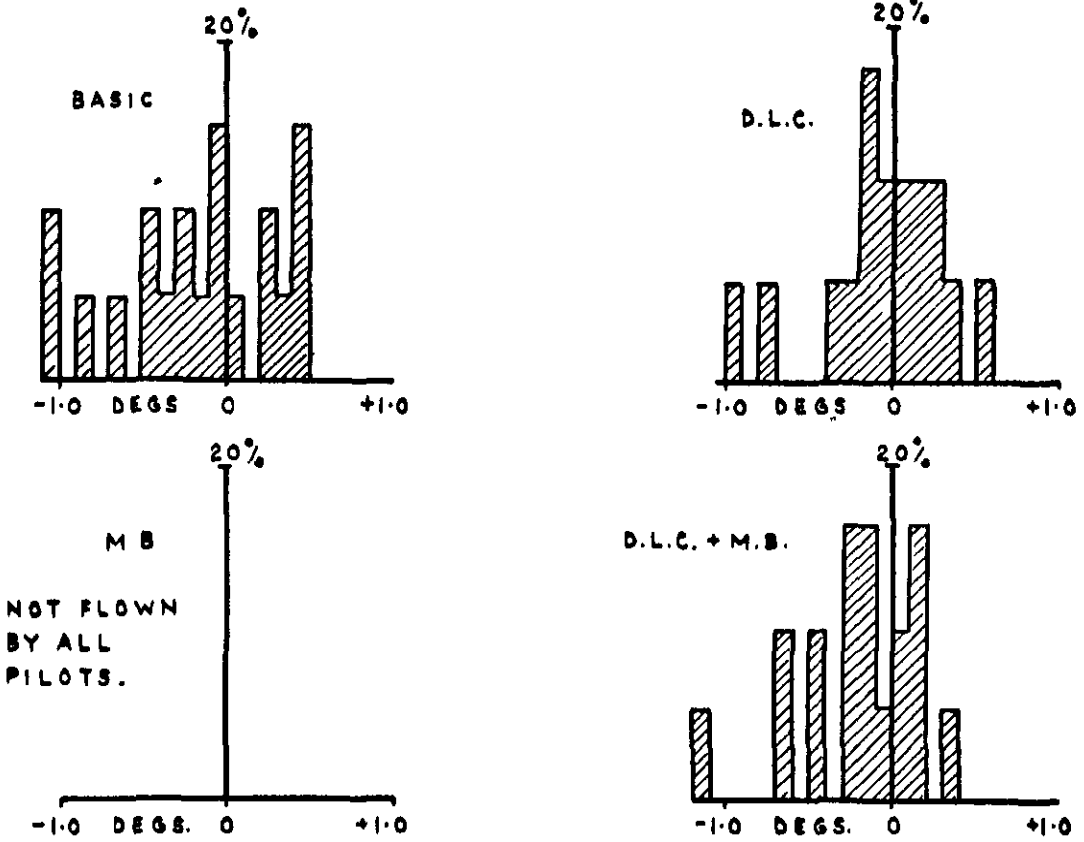
FIG 13

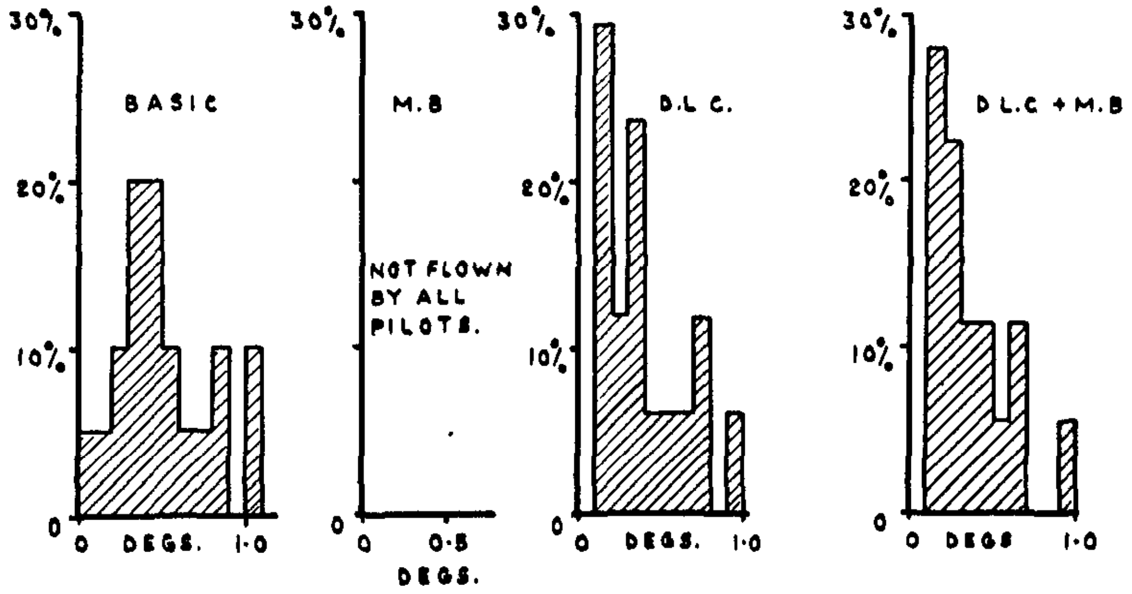
HISTOGRAM OF MEAN ERROR & MEAN MODULUS IN ELEVATION

FWD. C.G.

MEAN ERROR.



MEAN MODULUS

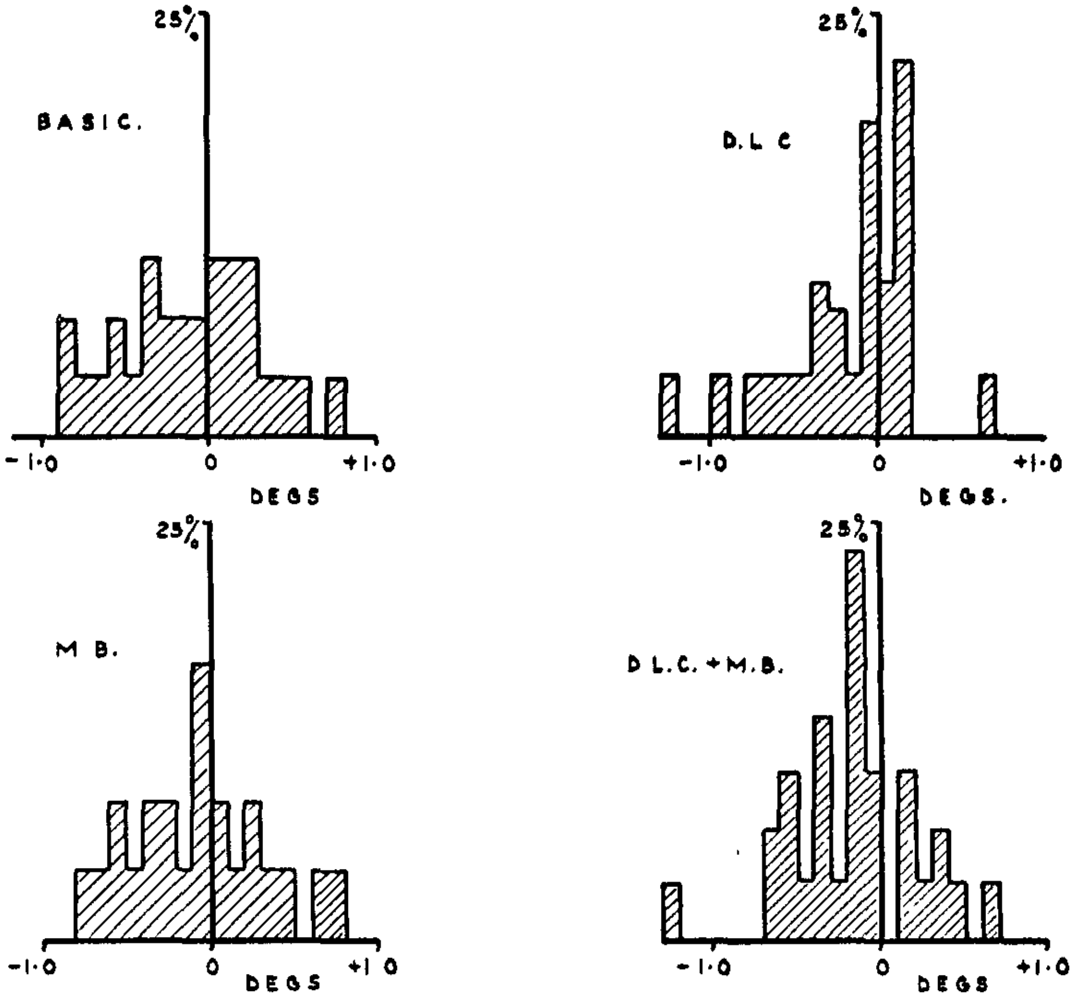


HISTOGRAM OF MEAN ERROR & MEAN MODULUS IN ELEVATION

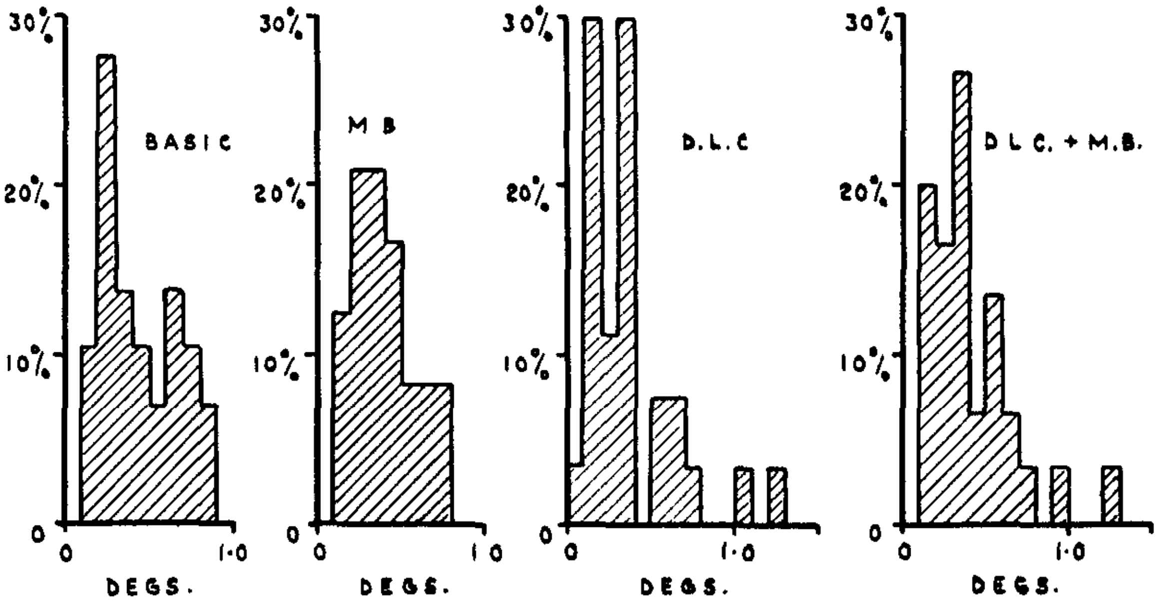
AFT C.G.

FIG.14

MEAN ERROR

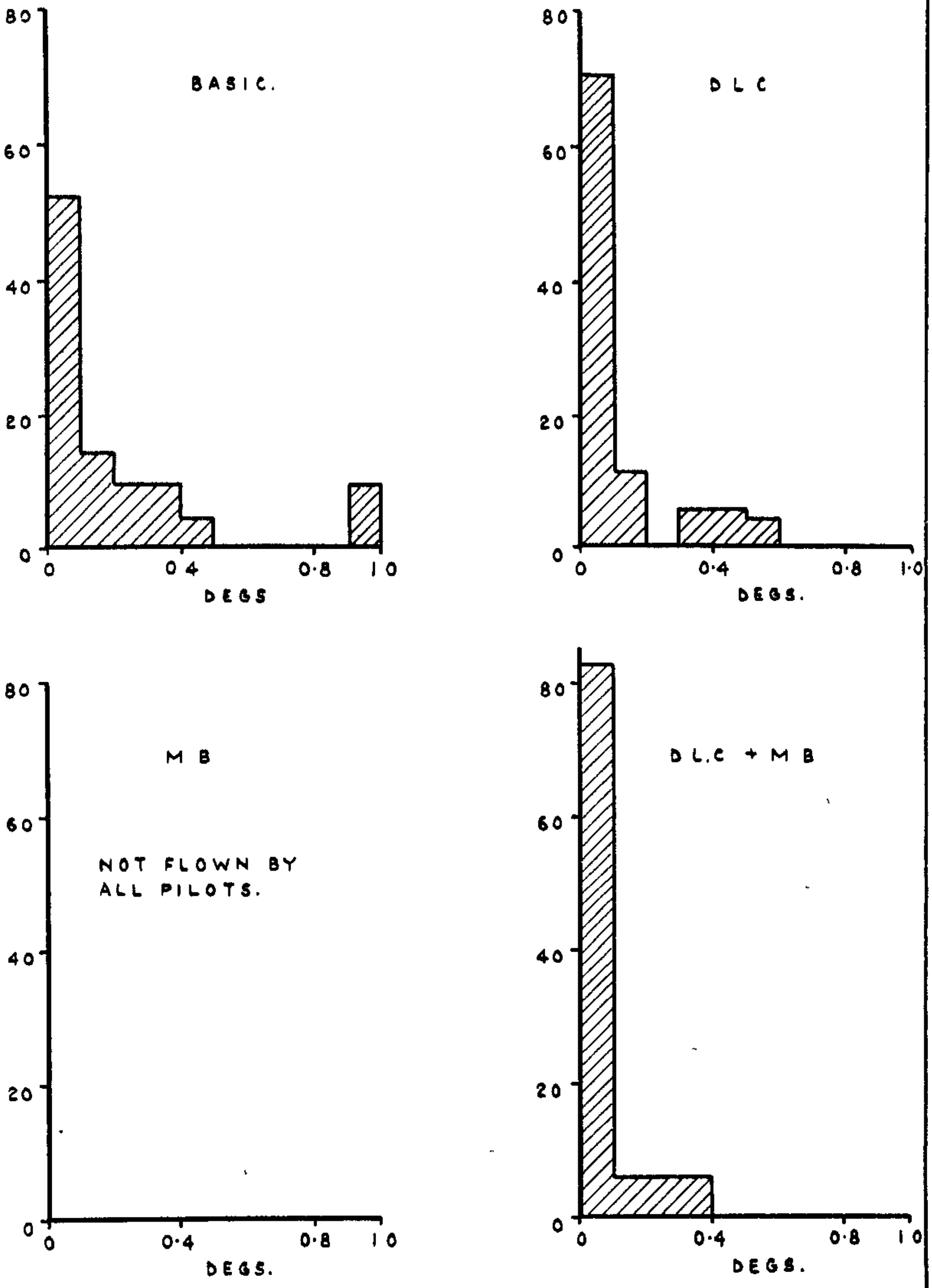


MEAN MODULUS.



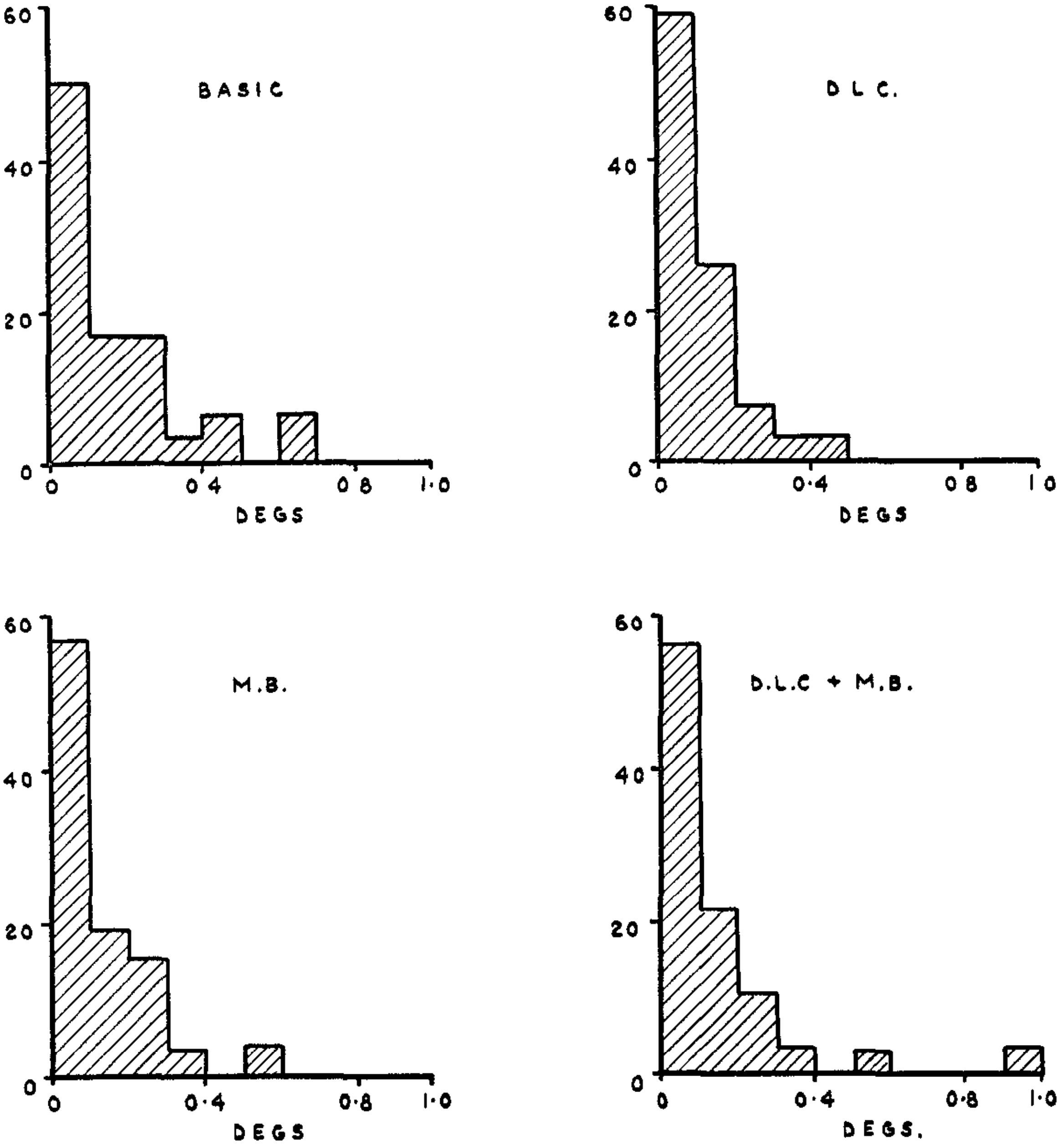
HISTOGRAM OF STANDARD DEVIATION IN ELEVATION

FWD C.G



HISTOGRAM OF STANDARD DEVIATION IN ELEVATION

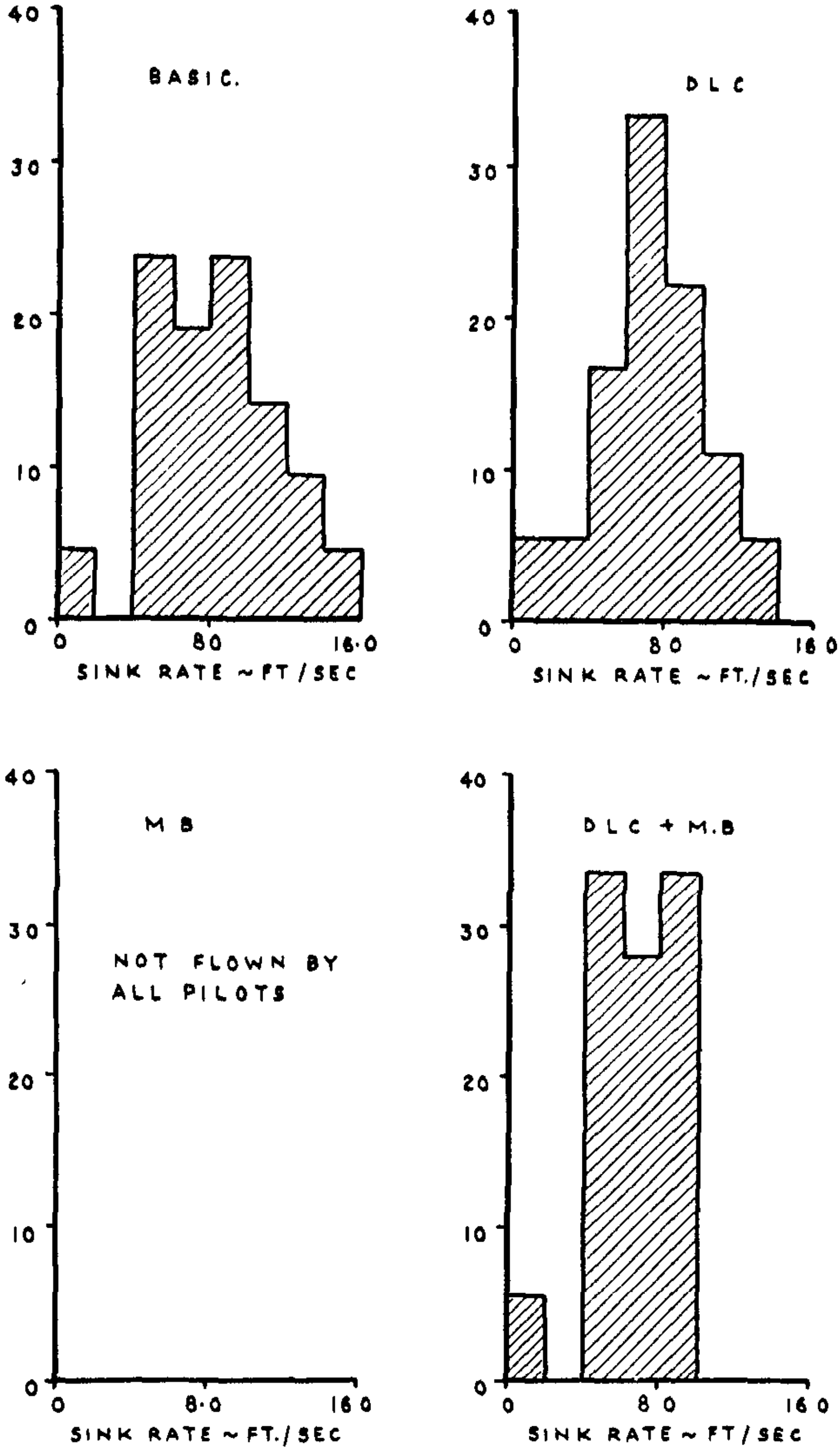
AFT C.G



Ae 312
FIG. 17

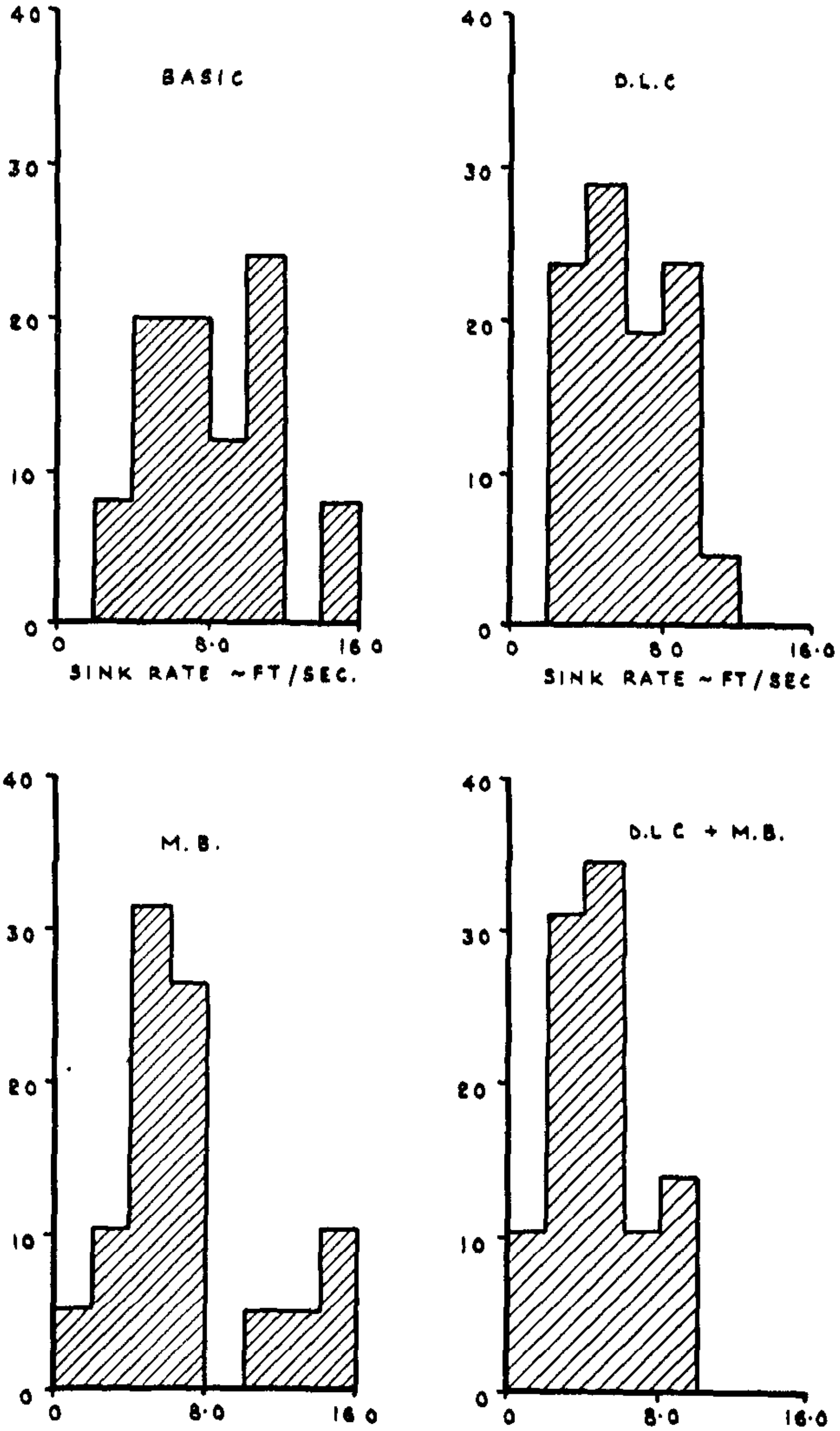
HISTOGRAM OF SINK RATE ON TOUCHDOWN

FWD C.G.

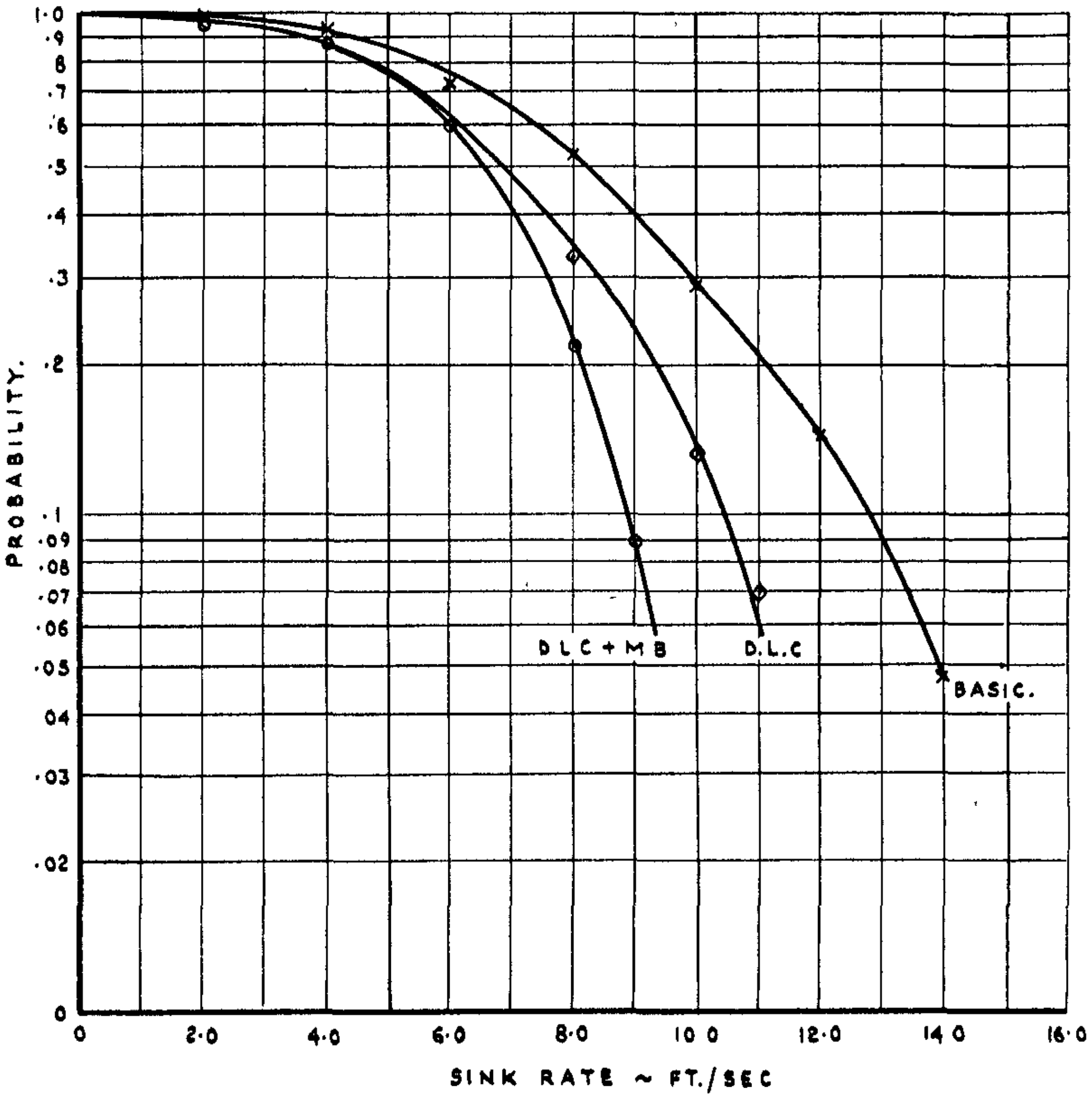


HISTOGRAM OF SINK RATE ON TOUCHDOWN

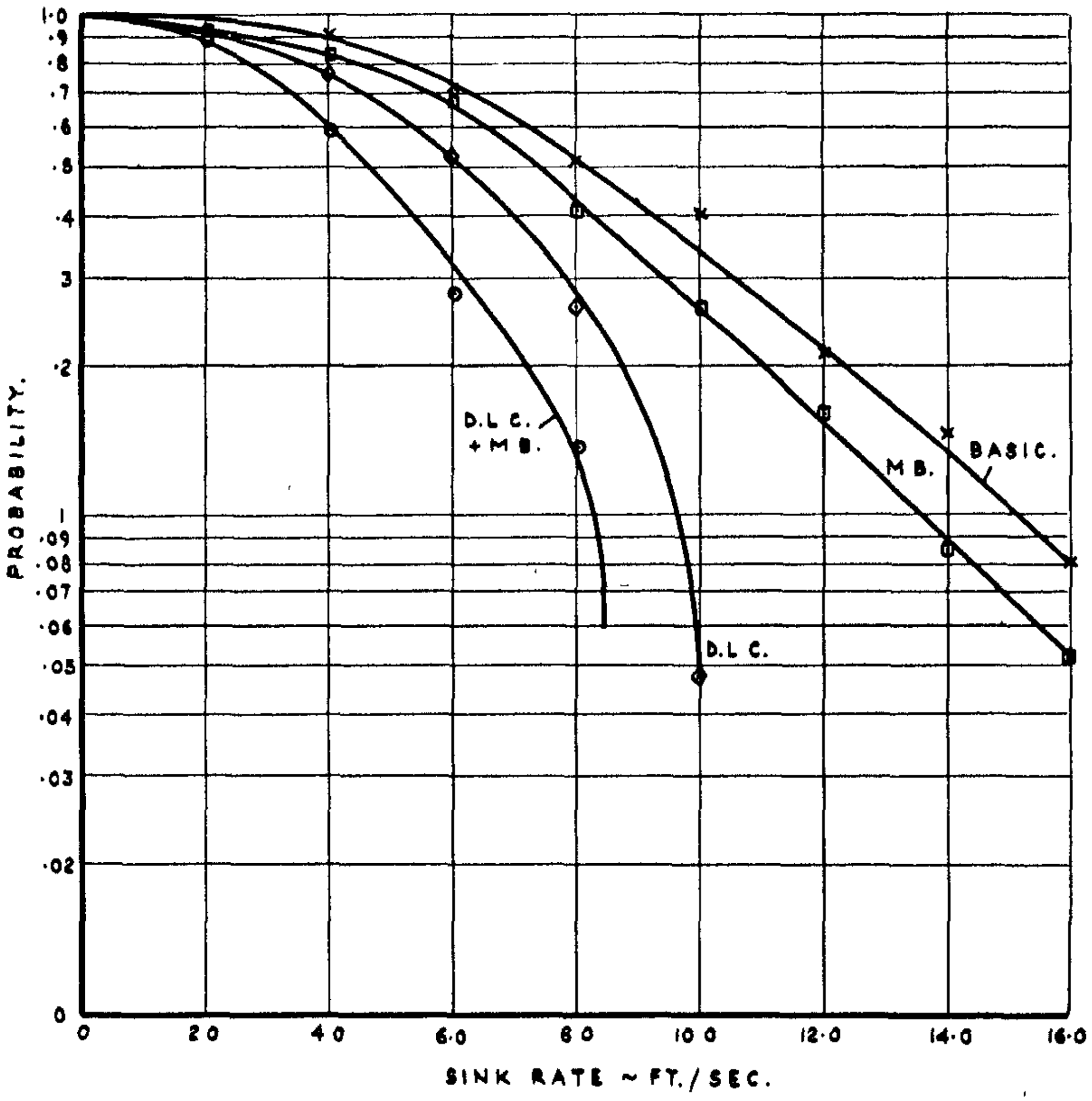
AFT. C G.



SINK RATE PROBABILITY CURVE
FWD C G.



SINK RATE PROBABILITY CURVE
AFT C.G.



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