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Some advantages and disadvantages of variable and Non-Linear Gearing between the Pilot's Control and the Control Surface

by

D. A. Lang, B.A.

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Some advantages and disadvantages of variable and non-linear gearing between the pilot's control and the control surface

by

D. A. Lang, B.A.

Summary

The advantages and disadvantages arising from the use of variable and non-linear gearing are considered, mainly in relation to a reduction of the pilots control movements required during an approach under bumpy conditions, to reducing over-sensitivity of control at high speed and mitigating the effects of friction and backlash.

Many complaints of control difficulty can, of course, be attributed to defects in the design of the control system e.g. friction and backlash in the control runs of either manual or power operated controls; friction and backlash in the force feel system, excessive centering force or unsuitable feel system on power controlled aircraft. Assuming that the obvious steps have been taken to eradicate these defects, then some further improvement in respect of sensitivity may be obtained by the use of non-linear gearing and the disadvantages are not considered serious provided that the degree of non-linearity is kept reasonably small.

With power operated controls, greater advantage can be obtained by the use of variable gearing. Because of the mechanical complication involved in systems in which such gear change is controlled automatically from airspeed, undercarriage or flap operation, a gear change directly under the control of the pilot is preferred whenever possible. On the rudder and elevator control it may, however, be necessary from safety considerations to link the gear change to undercarriage or flap operation. A pilot operated gear change gives positive advantage in that he can select appropriate gearings for different operational tasks and weather conditions, but reflects on present methods of safeguarding structural strength. With pilot selection it may therefore be necessary to restrict the range of gear change used if the aircraft structure is to be safeguarded and if limitations are not to be put on the control surface angles that can be used at high speed or Mach number.

By combining some measure of variable and non-linear gearing and by careful design to avoid friction and backlash effects it should be possible to overcome most of the difficulties that are likely to arise for some time to come.

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1. Introduction

On aircraft in the past there has usually been a constant linear gearing between the pilot's control stick, wheel or rudder pedals* and the corresponding control surface. With increase of the range of airspeeds over which modern aircraft are required to operate, complaints are sometimes made, either that control of the aircraft is unduly sensitive at high indicated airspeeds (i.e. that very small movements of the stick give very large effects in rate of roll, pitch or yaw) or alternatively that excessively large stick movements are required at low speeds, primarily during approaches under bumpy air conditions or on Naval aircraft during approach to a carrier where control is likely to be difficult because of the low approach speed. These two complaints are in the main, different facets of the same problem, the problem of providing the desired control characteristics over a large speed range with a constant stick to surface gearing; the problem is, however, aggravated if in addition the surface effectiveness falls off at slow speed due to aerodynamic causes. It is also aggravated on power controlled aircraft, by many of the defects that are common on power control systems e.g. friction, backlash, high centering forces etc.

It is possible that an improvement in the characteristics complained of might be obtained in certain cases by a straightforward modification to the gearing between stick and surface. For example, on an aircraft with a manual control system, the gearing may have been chosen to give desired stick forces rather than desired stick movements. By altering the surface aerodynamic balance and the gearing it might be possible to obtain reasonable values of both forces and movements. Secondly, on an aircraft with very effective controls, the effectiveness throughout the speed and Mach number range may be higher than is really necessary. In this case a lowering∅ of the gearing may be acceptable.

If, however, alleviation by such means is impossible and on power controlled aircraft, improvements to the power control and feel system prove ineffective then it may be necessary to use a non-linear or a variable gearing between stick and control surface; with future increases of indicated speeds, the need for such devices is likely to increase. The object of this report is to consider the various possible applications of these non-linear and variable gearings, their relative merits for different applications and any disadvantages or dangers in their use.

2. Possible methods of incorporating non-linear or variable gearing into control systems

The various methods of incorporating a non-linear or variable gearing in a control system are given in tabular form below. These sub-divisions are of importance since they lead to different relationships between stick force and displacement and have various advantages and disadvantages.

/Table 1.....

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* To avoid constant repetition, the pilot's control will be referred to as a stick throughout the remainder of this report. In general, however, the remarks will apply equally to all controls, unless specifically excluded by the text.

∅ A low gearing implies, in this report, a large movement of the stick for a small movement of the control surface.

Table 1

Basic type of control	Manual or power boosted control system		Power operated control system					
Type of gearing	Non-linear	Variable	Non-linear			Variable.		
Position of non-linear or variable gearing in relation to aircraft feel system	No feel system hence variable gearing can be put anywhere in circuit.		Output side from power control servo	Input side to power control servo: Before input from artificial feel unit	Input side to power control servo: After input from artificial feel unit	Output side from power control servo	Input side to power control servo: Before input from artificial feel unit	Input side to power control servo: After input from artificial feel unit

In this table, the term non-linear gearing means that the gearing between stick and control surface varies over the range of movement of the stick. The non-linearity will usually be such that a large movement of the stick is required for a small movement of the surface for control positions around the central position, in the case of the aileron and rudder and near the position for steady cruising flight in the case of the elevator. The ratio of stick to surface movement would then decrease progressively towards both extremes of the range of movement. An illustrative example of the relative movements of stick and surface that might be used is given in Fig. 1. The degree of non-linearity could, of course, vary over a wide range, being limited only by possible mechanical difficulties for large degrees of non-linearity and as is shown later, by heavy control forces in some applications.

In the case of variable gearing, the gearing between stick and surface remains constant as control angle is varied, but the gearing may be altered by schemes such as:- (i) By a direct control from the pilot. (ii) By a servo system controlled by indicated airspeed or possibly by a combination of indicated airspeed and altitude. (iii) By linkage with the undercarriage or flap operation. In the case of (ii) and (iii) the gear could be a two position one and in the case of (i) and (ii) a multi-position one, or could be continuously variable. The respective merits of various of these schemes are considered later in this report.

3. Resulting stick forces and movements

The stick forces and stick movements required for various control surface movements have been worked out, using very simple assumptions, for two speed conditions, a high and a low speed condition, the ratio of the high to the low speed being assumed to be 6:1 (roughly the ratio of maximum to minimum speed being obtained on present day fighters). For the variable gear curves, two gears in the ratio of 2½:1 have been assumed (Fig. 2). For the non-linear gearing, the aileron stick-surface relationship of Fig. 1 has been used. This gives a gear ratio of half the linear gearing at the mid-position and twice the linear gearing at the extremes of travel.

In the case of manual and power boosted control systems, it has been assumed that the control hinge moment coefficient does not vary with indicated speed. This assumption is obviously not true in practice over such a large speed range, but since the resultant figures are intended to be illustrative only, the assumption may be adequate for this purpose. For the power operated systems, curves have been calculated for various feel systems: simple spring, force varying with V and force varying with V^2. Arbitrary force scales have been added to the figures to show the order of the force variations that might be obtained.

/The results.....

The results are shown in Figs. 3 to 11. Each Figure gives, in addition to the curves of force variation, diagrammatic sketches of the control layout and formulae for the force variation with displacement. In the main the results (Figs. 3 to 9) apply to an aircraft without friction and backlash in the control system. In addition, results are given in Figs. 10 and 11 with these effects included. In drawing up these curves it has been assumed that the majority of the friction and backlash will arise in the control runs from the base of the stick to the power control servo motor and in the servo motor valve. On most present day aircraft, where the power control motors are situated near the control surface, this assumption will normally be true. Friction forces on the output side from the power control do not, of course, affect the pilot's control forces.

The curves have been included in the Report, as it is considered that they will be of general interest, since they indicate what force variations will be obtained from various types of installation. It is obvious that some of these installations can be ruled out, since they give characteristics diametrically opposed to what is required. The optimum layouts for various control problems are considered in greater detail in the remainder of this report.

The results are drawn for the aileron control and for movement in one direction only, since the curves are symmetrical. Similar curves would be obtained for the other controls.

4. Reasons for wanting variable or non-linear gearing and methods of obtaining required characteristics

4.1. General

4.1.1. Manual controls. On an aircraft with manual controls, it may be shown that, making many simplifying assumptions, and assuming that there is no control distortion, compressibility effects or spring tabs, the control force for a given control angle will vary as V^2 and that the control force for a given steady rate of roll will vary with V. At the same time, assuming control effectiveness not to vary with control displacement, the control angle for a given rate of roll will vary inversely with speed. It is known that on such aircraft, the control forces at high speeds are higher than pilots like and it is probable that they would prefer the control force for a given rate of roll to remain constant. (1). There is some evidence from aircraft on which variable gearing has been fitted, that they would prefer also a more nearly constant value of stick movement per unit rate of roll. On these assumptions it would be possible to achieve both of these aims by making the gearing between stick and surface vary inversely with V. The simplifying assumptions made above are unlikely to be true in practice. Even so, it may be possible by suitable choice of variation of gearing with speed to obtain much more nearly the desired force and movement characteristics than is given by a normal fixed gearing. Similar arguments apply on an aircraft with power boosted ailerons.

4.1.2. Power controls. On an aircraft with power operated controls, using similar assumptions, the same result can be obtained by using a gearing varying inversely with V in conjunction with a simple spring attached to the stick. For aircraft on which the response to aileron movement did not conform to the simplifying assumptions made above, it is nevertheless possible that a combination of a variable gearing with a simple spring would give roughly the desirable forces and movements over the speed range. Because of the probable fall of effectiveness at high speeds, a smaller gear change than is suggested by the simple theory would probably be required and this would obviously make the design of the variable gearing easier.

Similar arguments apply to rudder and elevator movements in terms of rate of yaw and rate of pitch. From structural considerations, however, it is desirable that stick force should bear some constant relationship to applied normal acceleration, rather than rate of pitch, as speed is changed. This characteristics could, of course, be obtained by a straightforward 'q' feel system with constant gearing, if compressibility and distortion effects can

/be ignored.....

be ignored. If, however, a constant rate of pitch for a given stick movement at all speeds is considered desirable, then a constant stick force per 'g' could be obtained at the same time by a combination of a variable gearing inversely proportional to V with a stick force per unit stick movement proportional to V. This would, however, be obtained at the expense of greater complication.

The need for variable gearing is likely to be increased for aircraft which are to operate in the transonic region. Because of the decrease of control effectiveness and the increase of manoeuvre margin in this range, large control surfaces with large movements are required to give adequate control. The controls are therefore likely to be over-effective for higher indicated speeds but lower Mach numbers. A lower gearing between stick and surface may therefore be desirable for conditions below the transonic speed range.

4.1.3. Other considerations. From the foregoing it will be seen that if it can be assumed that appreciable stick movements are essential for accurate control there are reasons on general grounds for supposing that a variable gearing between stick and surface may give a feel system more in accord with what the pilot would like than is possible with fixed gearing and that it might therefore give greater precision of control throughout the speed range. A further possible advantage of variable gearing is that pilots might wish to select a different gearing for different operational tasks. For example the gearing that the pilot would like for an attack under radar control at night might well be quite different from what he would like for combat under visual conditions. Similarly the pilot might prefer a much lower gearing for a bombing run under manual control at high altitude, compared with what he would like for say a climb through cloud at the same indicated speed at low level. For the pilot to take advantage of this facility, gear selection would, of course, have to be under the pilot's control throughout, or he would have to be able to override any automatic selection.

Against all this, there is a considerable body of opinion that the amount of control movement is of relatively minor importance, the major factor of which the pilot is aware being the control force, and that optimum control characteristics are, in fact, obtained by using a pure "force control", in which movements of the control are negligibly small. If this view is accepted, then there is no general case for variable gearing but rather for the development of pure force controls.

However, the evidence in favour of the latter is not yet conclusive and aircraft will continue to have orthodox controls for some time to come; it is useful therefore to consider certain conditions about which complaints are often made and to consider which of the possible variable and non-linear gear schemes would give the greatest improvement.

4.2. Too large stick movements required at slow speeds or for landing.

4.2.1. General. Complaints are sometimes made on certain aircraft that excessive control movements are required at slow speeds or for landing, particularly under bumpy air conditions. The complaints are particularly relevant to the carrier landing case, because even when conditions are turbulent, it is still necessary to make the approach at a very slow speed, where aileron effectiveness is likely to be fairly low. With such turbulence, the pilot may make frequent large movements of the stick to deal with the wing dropping that occurs. It is obvious that the difficulty of making these movements will vary with the stick forces, the heavier the forces the more tiring and difficult it is to make large movements. If either the forces or the stick movements are reduced the condition might be acceptable, but evidence suggests that even with low forces pilots do not like to have to make frequent large stick movements during the approach.

4.2.2. Manual controls. The advantages accruing from variable gearing may be considered for various types of aircraft control systems. Firstly on aircraft with manual or power boosted controls it is seen from Fig. 3 that a change of gearing in addition to reducing the stick movement also

/increases.....

increases the stick force per unit surface movement. If the initial control forces were light, then this increase of control force may be acceptable. However, in many cases it is probable that the heavier control forces may be as objectionable as the large stick movements and if acceptable control characteristics are to be obtained it may be necessary to increase the balance of the control surface. Since presumably efforts will already have been made to obtain light control forces, increasing the balance is not likely to be easy and it is therefore doubtful whether a change of control gearing will be practicable as a general rule on manually controlled aircraft.

A non-linear gearing might also be used to reduce the stick movement required for large surface movement. To achieve this, the gearing would be kept the same as the linear gearing at the central position, but would be increased towards each side. Thus, for small movements of the control about central, the stick forces would be virtually unchanged and hence the forces required for manoeuvring at high indicated speeds would only be slightly increased. Such a gearing might obviously give some improvement, but it is not likely to be so effective as a variable one and it will have the same limitations with regard to the increase of control heaviness.

4.2.3. <u>Power controls.</u> On aircraft with power operated controls, various combinations of force and movement can be obtained, as will be seen from Figs. 4 to 9. With the feel forces fed direct to the stick before the variable gearing, reducing the stick movement also reduces the stick forces required. With simple spring feel, and assuming that the low gearing is used at high speed and the high gearing at low speed, this will give an improvement in control characteristics both in respect of movement and force, since the control forces can be made lighter at low speeds without decreasing the forces at high speed. Such a system might therefore be used instead of, for example, a V or M controlled force feel system. If the change of gearing was directly controlled by the pilot, then the system would probably be simpler than the equivalent force feel system. If, however, the change of gearing were automatically operated, then undoubtedly greater complexity would result.

A similar result might be obtained by the use of a non-linear gearing, if the gearing is retained at its original value over the central portion of the motion and increased over the extremes of travel, so that the overall stick movement is decreased. In this case, the force for small surface movement would be unaltered, but the force for large movements would be reduced. Thus at high speeds, where in general only small to moderate movements of the surface will be required, the forces will remain reasonably heavy, but at slow speeds where large control movements are used the forces would be relatively lighter for large control surface movements than when the linear gear is fitted. However, since the force is still a linear function of stick movement, the pilot will probably be unaware of the non-linearity.

If the artificial feel forces are fed in after the gear change then it will be seen from Fig. 5 that when the stick movement is decreased the control forces are increased as in the manual control case. Assuming as before that the low gearing will be used at high speed the control force per unit control surface movement will be heavier at low speeds than at high speeds and these heavier forces may limit the stick movement that pilots are willing to use. In the same way, a non-linear gearing before the feel forces are fed in, will give heavier forces for large control movements and will suffer from the same disadvantages.

It is evident from this that for this case a variable or a non-linear gearing, with feel forces fed in before the gear, will give the optimum feel characteristics. Of these, the variable gearing will give more nearly linear response against stick movement and a better relationship between forces at low and high speed and is therefore to be preferred. Since the large control movements are required only at slow speeds, a two position gearing could be fitted manually controlled by the pilot. As an alternative, if only required for the approach, the gear change could be linked to the flaps or undercarriage operation.

/The remarks.....

The remarks made above have related primarily to the aileron control. Similar difficulties are possible on the rudder control, since rudder may be used to help raise a dropped wing on the approach. However, no cases of complaint have occurred to date and on general grounds it is less likely that trouble would arise from this cause than on the aileron. However, if difficulty was experienced the same methods could be used.

On the elevator, large movements are required only on the actual round-out and providing full stick movement can be obtained in this condition, little difficulty is likely with the stick movements required at slow speeds, unless these are associated with heavy forces.

4.3. Over-sensitivity at high speeds

4.3.1. General. Over-sensitivity at high speed is a different facet of the same problem discussed in para. 4.2., since the gearing chosen initially is a compromise between the conditions required for high and low speeds and a solution satisfactory for one end of the speed range, will automatically ease the problem at the other end of the range. However, it is useful to consider the application specifically to this case.

4.3.2. Variable gearing. On a manually or power boost controlled aircraft, increasing the stick movement by reducing the gearing will give decreased forces at high speeds. Since, in general, the force required for a given manoeuvre (e.g. rate of roll or pitch) is greater at high speeds than at low, and often heavier than desired at high speed, variable gearing will give a desirable reduction. Hence a reduction in gearing will almost certainly be beneficial both from considerations of stick movement and stick force.

On an aircraft with power operated controls with the feel force fed direct to the stick, it will be seen from Figs. 4, 6 and 8 that decreasing the gearing gives an increase of force for a given control surface movement. Thus if a simple spring feel system is used a beneficial increase of control force per unit surface movement will be obtained at high speed. Since the oversensitivity is likely to be progressive with increase of speed, a progressive decrease of gearing with airspeed is desirable, with allowance for Mach number effects where these are important. An automatic change of gearing, operated from airspeed pressures is therefore indicated. With such a system it would be possible to get desirable combinations of movements and forces, without recourse to more complicated force feel systems.

With the feel forces fed in after the gearing, a reduction in stick gearing gives a decreased force. With a variable gearing, speed controlled and with a simple spring feel, the force for a given control movement will decrease with speed. To obtain satisfactory control forces on such a system, it would be necessary to have a feel system such that force increased roughly as V^2. Although this might be acceptable, it would obviously be more complicated that the simple spring attached to the stick considered above.

A further effect of variable gearing is that if maximum available stick movement is kept constant, then decreasing the gearing will reduce the aileron angle that can be applied. On some aircraft where there is a stressing limit on the use of ailerons at high speeds, this may be advantageous since control angles can be kept within design limits without the necessity for heavy control forces. Where, however, there is no stressing limit on the ailerons, such a restriction on aileron movement might impose limitations on the aircraft's rolling capacity at high speeds and Mach numbers particularly if the control effectiveness falls off. This would be objectionable operationally and might well be dangerous.

4.3.3. Non-linear gearing. As an alternative to these variable gearing schemes, a non-linear gearing might be used. On a manually or power boosted aircraft, this would give relatively lighter control forces over the central portion of the travel, with relatively heavier control forces for large control movements. Provided that the degree of over-sensitivity was not great, and hence that only moderate non-linearity was required, satisfactory control characteristics could probably be obtained by this means. Further

/flight....

flight experience is necessary before a definite statement can be made on how much non-linearity can be used before the control characteristics become objectionable.

With power operated controls, the force variation over the range of movement will depend on where the feel force is fed into the circuit. With a spring attached directly to the stick, the force per unit surface travel will be heavier for small movements than for large ones; when the force is fed in after the gearing the force per unit surface travel will be lighter for small movements than for large ones. The latter condition is probably preferable, provided that the spring force is suitably varied with speed (e.g. varying as V) although this does mean that the force per unit stick movement is non-linear. As in the manual control case, control characteristics will probably be satisfactory provided only moderate non-linearity is used.

4.3.4. Rudder and elevator control. On the rudder similar arguments will apply but since the rudders are used less frequently than the ailerons, and large rudder angles are normally only used at low speeds, a variable gearing is probably not justified and a non-linear gearing may be the best solution in this case.

It is doubtful whether the restriction that a variable gearing is likely to place on the available movement of the elevator would, in general, be acceptable, particularly in the transonic region, although there may possibly be applications as for example, on high altitude transport aircraft on which rapid manoeuvring is not required, where such a gearing might give satisfactory control characteristics. On other types of aircraft, the only simple improvements to the longitudinal control that could be obtained, assuming that these aircraft already have the optimum force feel system, would seem to be some measure of non-linearity of gearing between stick and elevator or, if this is insufficient, as a further extension of the same idea, a non-linear gearing between elevator and tailplane movements.

4.4. Friction and backlash. Difficulty of control can often be attributed to friction and backlash (2), particularly on aircraft with power operated controls. Adverse characteristics can arise in a number of ways. Firstly, if friction is present, then a corresponding spring centering force is necessary. Assuming friction is high, this means that a large force is necessary to move the control. A further small increase in force may then cause a large control movement. The effect may be even worse if, as is quite likely, the friction force decreases as soon as the control starts to move. Secondly, with backlash present in the control runs to the power control valve and in the valve itself, a small movement of the stick, which may require a large force as explained above, gives no control movement, but a further small movement with light forces may produce a large effect. In addition there may be appreciable backlash in the linkage to the feel system. If the lost motion is greater then in the control run and valve, then it may be possible to make small movements of the control surface, without having to overcome the centering spring force. Small movements are made against friction only and precise control is then likely to be difficult.

It is obvious that the best way of overcoming control difficulties due to these causes is to make the friction and backlash as small as possible. It may not, however, be practicable to eliminate all adverse effects by these means. Further improvements may be possible by modifications to the aircraft feel system (e.g. by increasing the spring rate and hence increasing the ratio of total force required for a given control movement to breakout force). It is useful to consider, however, what improvements may be effected by use of a variable or non-linear gearing.

With friction in the circuit and a variable gearing at the stick, a reduction of gearing would give a proportionate decrease in the friction force felt at the stick, since the majority of the friction will be in the control runs and valve mechanism. Some improvement in control characteristics in low gearing might therefore be expected. For maximum improvement, the feel system should be attached before the gearing so that the ratio of friction to feel force will be reduced.

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With backlash present, the advantages of a variable gearing system are less obvious. With the gear at the stick, a reduction in gearing will give proportionately equal increases in the stick movement necessary to overcome backlash, and that required to move the control surface through the desired angle. (Fig. 10). This is likely to make control more difficult because of the increased backlash region. When backlash is present in the linkage to the feel system, some improvement may be possible by putting the gearing between the feel system and the power control valve, since in low gearing there will be less possibility of obtaining control surface movement without encountering the spring centering force.

Backlash effects could, however, be reduced by fitting the variable gearing on the output side from the power control, since the ratio of backlash to total stick movement required would be reduced (Fig. 11). Where friction and backlash are both present the best position for the gearing will be determined by the relative importance of the friction and backlash contributions to the adverse characteristics. However, it would appear that a variable gearing after the power control must always give some improvement of characteristics.

Similar arguments apply for a non-linear gearing. This may be expected to reduce the over-sensitivity at high speed, provided that it is put in at the right point in the circuit. As with the variable gearing, the best position can only be fixed by considering the relative importance of friction and backlash.

4.5. Manual reversion case. On power controlled or power boosted aircraft in which emergency control is provided by manual reversion, an improvement in control in the emergency case might be obtained by use of a variable gearing under the control of the pilot. On such aircraft controllability is usually limited by the heaviness of the forces required. If this means a serious practical limitation on the control angles that can be applied, then it might be possible to improve the control characteristics by reducing the gearing. This would, of course, mean that larger stick movements would be necessary for a given surface movement, but it would also mean that the force required would be reduced and the maximum control angle that could be applied would be increased, provided that this is not restricted with the reduced gearing. Although these large stick movements are undesirable as a general rule, they may be more acceptable than heavy forces for the emergency case. It is not possible to say whether it is likely to prove advantageous as a general rule as this will depend on the aircraft control characteristics.

5. Possible dangers and disadvantages of variable gearing

5.1. Risk of failure of gear change mechanism

5.1.1. Pilot operated gear change. In the various applications of variable gearing mentioned above, both manual and automatic changes of gearing are considered. Failures of two types can therefore arise. In the first case, the pilot might forget to select the right gearing for landing or for high speed flight. As a result it is possible to envisage cases in which the pilot will find himself with inadequate aileron movement for landing or even if sufficient aileron movement is available, he might make too small a corrective movement because he is in low instead of high gearing. Similarly at high speed he might overcorrect if he was in high instead of low gearing.

Obviously the control system must be such that it is impossible to overstress the aircraft whatever gearing is selected. In some cases this will be covered automatically e.g. the ailerons and wings may be stressed for full aileron movement at all speeds or aileron movement may be limited by 'q' controlled stops. Recent experience suggests that on the aileron control one or other of these methods will be used in the majority of cases. On the rudder this is unlikely to be true, although stops moving as some function of 'q' could be used if desired. However, as was explained earlier, there is at present no obvious need for variable gearing on the rudder control. In the pitching plane it would be very difficult to ensure that the normal

/stick force.....

stick force per 'g' requirements were not in all gearings. On a fighter with an n_1 of 8, this would probably not be very important, since the chances of inadvertently over-stressing the aircraft would be small. On aircraft with lower n_1 values it would be necessary to rely on readings of a visual accelerometer or on a 'g' restrictor if such were available. Although a visual accelerometer may well be acceptable as a structural safeguard in some cases, a pilot controlled variable gearing to the elevator is likely to be of only limited application for these structural reasons and the reasons given in para. 4.3.

The degree of hazard involved on any of the controls is obviously a function of the change of gearing used. For large gear changes (i.e. 3 or 4 to 1) the hazard would obviously be a very real one, as the pilot might not realise his error until excessive accelerations had been applied or until he had run out of available control movement under bumpy air conditions near the ground or carrier and it is almost certain that such a system would be unacceptable for general Service use. However, if the gear change is small (say under 2 to 1) then the dangers involved would be reduced and depending on the control characteristics of the aircraft, the control available even in the lowest gearing might well be sufficient to enable the aircraft to operate with reasonable safety even at slow speed close to the ground. In such cases a manual gear change would seem to be acceptable.

5.1.2. <u>Automatic 2 position gear change.</u> An alternative to the pilot controlled system for such small gear changes would be a mechanical control operated at a given airspeed or in conjunction with undercarriage retraction. With a simple gear change mechanism, it would be possible for a change of gearing to give a sudden control surface movement and this might well be dangerous. It would probably be possible to overcome this in a number of ways. For example, the gear change could be made to take place gradually over several seconds or, on the ailerons, only when the control was in the central position. On the elevator the most promising solution would seem to be to make the point of zero control surface movement as gear was changed move with the trimmer and then to have a device that would only allow the gear to change when the aircraft was in trim. All such systems would obviously involve some mechanical complication and there would therefore be some risk of failure. The greatest danger in this case would probably be if in the event of failure, the mechanism automatically changed gear (e.g. the system might be preloaded to return to the landing condition). If such an automatic change occurred with aileron elevator or rudder on, there might be some hazard, as for example in formation flying or a ground attack. A system that failed in such a way that the mechanism stayed in the gear selected at the moment of failure, with an emergency manual selection of the landing gearing would seem to be the best solution. In view of the complication involved, a pilot controlled system is likely to be preferred, at any rate on the aileron control, in view of the other advantages, mentioned in para. 4, that it confers. Where a pilot controlled system is unacceptable for reasons mentioned above, then it would be necessary to use an automatic system with adequate safeguards against failure.

5.1.3. <u>Airspeed controlled gear change.</u> For large changes of gearing, it is very doubtful whether the pilot can be relied upon to make the correct selection of gearing. This will be particularly important if stick forces or movements are being relied upon to safeguard the aircraft structure. In such cases, it would seem to be necessary to have some means of automatic gear change, preferably operated off the aircraft A.S.I. pressure system. Unless the gearing was controlled automatically, it would be almost impossible the the pilot to prejudge how much stick force or movement would be necessary for a desired manoeuvre. It is, of course, debatable how far the pilot relies on previous experience in determining the amount of control required for a given manoeuvre, but it is likely that when fully experienced on an aircraft type, precognition plays some part in accurate control. It seems probable, therefore, that without automatic selection, there would be some loss of flying accuracy.

/Because.....

Because of the dangers mentioned above, it would be necessary to ensure that the mechanism stayed in the gearing selected at the moment of failure, with a manual override for selecting the correct gearing for landing. It would also be necessary to provide a warning to the pilot that failure had occurred. Such a system would probably be acceptable, but it is evident that there would have to be very marked advantages accruing from the variable gearing to justify the added complication and the addition of yet another warning system to the pilot's cockpit.

5.2. Instability effects. If a gear change is fitted in the elevator circuit, automatically controlled from the A.S.I. system, then the simple system may lead to instability. This can be seen from Fig. 12. If the line ABC shows the relation between elevator movement and stick position and if the elevator position for trim is given by point D, then if speed decreases slightly, the elevator to stick gearing will change and the elevator will move up from position D to position D'. This elevator movement would cause a further reduction in speed and hence the speed would diverge towards the stall. Steady cruising might therefore be difficult. This difficulty could be overcome as far as the steady condition is concerned, by making the position at which no movement of the elevator occurs as gearing is changed (i.e. point B in Fig. 12) correspond with the trim position. This would entail linking the gear change to the trimmer. The normal static stability conditions would then apply.

However, this would not remove the difficulty as far as manoeuvring flight is concerned. In a pull-out or on entering a turn, the stick is pulled back to achieve the required normal acceleration. If then speed falls off, further up elevator will be progressively applied. It is admittedly true that as speed decreases a progressively larger elevator angle will usually be required to maintain a constant normal acceleration, so that the change is operating in the correct sense in reducing the progressive stick movement required. However in cases where the aircraft approaches neutral manoeuvring stability in a turn, this behaviour would be most undesirable since it would cause the turn to tighten progressively if speed was allowed to fall off. Since most present day swept wing aircraft show a reduction in manoeuvring stability in turns at high Mach number, such a variable gearing would undoubtedly aggravate the control problem and it is very doubtful whether it could be accepted. This problem is not, of course, insurmountable. The system could, for example, be such that a gear change could only take place when the elevator was in the trim position. However any solution seems likely to involve a good deal of complication.

Somewhat similar effects would be obtained on aileron and rudder controls, since as speed is reduced the aileron and rudder positions would automatically alter. However, the aileron and rudder angles required in the turn will in any event probably vary with speed, so this is probably not a serious objection.

5.3. Pilot may not know how much more control he has available. In certain circumstances the pilot may want to know how much more control he has available. For example, if an approach is being made with an extreme forward c.g. position (e.g. due to a bomb hang up or misuse of the fuel system) then on an aircraft without variable gearing, the pilot knows how much more elevator control he has available from the position of the stick at each stage of the approach. With variable gearing controlled from the airspeed system, either the range of stick movement remains constant, in which case the elevator angle for full movement of the stick will decrease with increase of speed; the stick may be almost fully back on the approach, but nevertheless the pilot might still have sufficient control available for landing, because of the increased control angle that would be available at the lower speed. Alternatively the range of stick movement will decrease with decrease of speed; in this case the pilot is likely to think that he has further control movement available when this is not so. In either case it will be more difficult for the pilot to estimate how much elevator control will be available for landing than with a fixed gearing. If the rate of gear change with speed is small, it is unlikely that this will lead to any very great difficulty in practice. With a large change of gearing, it might be necessary

/to restrict.....

to restrict the automatic operation to speeds above say 200 knots. Even without this, the pilot could, if in doubt, always carry out a check on the amount of elevator available, at a safe height, so that it is unlikely that this will prove a serious difficulty.

Similar arguments would apply to the rudder control on a landing under asymmetric power conditions and to the aileron when landing with an asymmetric fuel or bomb load.

5.4. Pilot loses some measure of ability to estimate speed. On aircraft in the past, the pilot has been able to make a rough estimate of his airspeed without recourse to his A.S.I. He has done this in part by an assessment of the control force required for a given stick movement, of the response of the aircraft to stick movement and also by an assessment of noise levels, buffeting, control tremors etc. With some of the schemes suggested, the forces for a given stick movement and the stick movement for a given response might be roughly constant over the speed range. The pilot would therefore be bereft of some of his means of estimating speed. Even so it is likely that the pilot will still retain some impression of speed since apart from the indications from noise levels, etc., it is unlikely that the response characteristics (i.e. acceleration in roll, steady rate of roll) will in fact remain constant over the speed range. The only time that the loss of ability to estimate speed is likely to be an embarrassment is when making an approach after failure of the airspeed system. However, provided that there is adequate pre-stall warning, this is unlikely to be of major importance and it is considered that any loss of ability to judge speed is of relatively minor importance.

5.5. Restriction of available control angle. If the change of gearing between high and low speed is large, either the stick movement at low speed has to be extremely small (i.e. of the order of 1 inch for full control surface movement) or else at high speed, full movement of the stick corresponds to less than full movement of the control surface. Since a maximum stick movement of 1 inch may well be unacceptable, it is probable that some restriction of the control surface movement would be inevitable. As explained earlier such restriction of control surface movement may give positive benefits on some aircraft on structural grounds. In other cases, restriction of the control angle might well restrict the manoeuvrability of the aircraft. For example, at high Mach number decrease of aileron or elevator effectiveness might mean that full control movement is required for adequate control and any restriction of control movement would be unacceptable.

With a lower change of gearing between the high and low speed conditions it may be possible to avoid unacceptably small stick movements at slow speeds while still retaining full control surface movement at high speeds; such lower changes of gearing are more likely to be satisfactory on fighter types of aircraft.

6. Disadvantages of non-linear gearing.

6.1. Force against surface displacement is not linear. From Figs. 3 - 11 it will be seen that the stick force per unit control displacement is non-linear, both on the manually controlled aircraft and also in the power control case whether the forces are fed in before or after the non-linear gearing. This would lead, for example, to a variation of stick force per g with applied g and a non-linear relationship between control force and steady rate of roll. A more or less constant relationship between control force and response has in the past usually be considered desirable. However, provided the non-linearity is not too great, the variations of response obtained would probably not be objectionable. In fact some relative increase in control force for large applied normal accelerations, rates of roll and yaw would probably have positive advantages from structural considerations. It will be seen from Figs. 3 and 5 that on manually controlled aircraft and on power-controlled aircraft where the artificial feel is fed in after the non-linear gearing, a force variation of this type is obtained. It will also be noted from those figures that there is a marked non-linearity of stick force against stick movement; this may possibly restrict the degree of non-linearity that can be used before adverse comment is made by the pilot.

6.2. Change of trim position with operating conditions. For the cruising flight case, if the non-linear gearing is to be effective in preventing control over-sensitivity, it is obvious that the centre of the low gearing range should coincide with the trim position of the stick. The elevator position for trim may obviously vary very considerably with changes of c.g. position, airspeed and Mach number. On some aircraft on which longitudinal trim is obtained by movement of the tailplane, the stick is always in the same position for trim and no difficulty will arise in this case. On other installations it should not be difficult to overcome the problem by linking the position of the non-linear gearing to the trim control, although some mechanical complication would obviously be involved. The linkages could, however, be entirely mechanical with no risk of failure and it is considered that any problems in this direction could be satisfactorily overcome.

6.3. Increase of stick movement required for landing. It is evident from Fig. 1 that the stick movement required for control angles less than the maximum will be increased by using a non-linear gearing, assuming that maximum movement is unaltered. This will increase the difficulty of control during the landing approach under bumpy conditions. However, for moderate amounts of non-linearity, this objection may not be serious provided that the overall stick movement is not excessive and stick forces are kept light. No difficulty is envisaged on the elevator control from this cause and on the rudder also, the effects are likely to be less adverse than on the ailerons.

7. Conclusions

The need for a non-linear or variable gearing is based on the assumption that stick and rudder pedal movements, as distinct from control forces are important for satisfactory control. If this were not so, then all control difficulties could be overcome by modifications to the forces fed to the pilots control. With friction and backlash present, appreciable control movements are necessary for satisfactory control and with conventional control systems, the magnitude of the control movements required for various manoeuvres over the speed range of the aircraft are undoubtedly important. However, even so, considerable improvements in feel can be obtained by reduction of friction and backlash and on power controlled aircraft by modifications to the force feel system. Non-linear and variable gearing systems should only be resorted to when other methods are unsuccessful or when positive advantages are gained with greater simplicity than would result from modifications to the force feel system.

Over-sensitivity of controls at high speed can be reduced by introducing non-linearity into the control gearing. No serious objections are seen to such a system, particularly on the elevator control, providing that only small degrees of non-linearity are used, and it may in fact give some improvement in feel characteristics by increasing the control forces required for extreme control movements. At the same time non-linear gearing can also provide some amelioration of the effects of friction and backlash.

With future increases in operating speeds, the advantages to be gained from non-linear gearing may be insufficient and it may therefore be necessary to consider speed controlled automatic variable gearing. However, the hazards and disadvantages are such that it is considered that these systems should be avoided whenever possible.

A more satisfactory solution, at any rate on the aileron control would appear to be the use of limited variable gearing directly under the control of the pilot using a mechanical system of gear change. In some cases, particularly on the elevator and rudder control, it may be necessary for safety reasons to link the gear change automatically to the undercarriage or flap movement and such a system should be acceptable provided the system is adequately safeguarded against failure. If a simple spring feel system is to be used on a power controlled aircraft, then this should be fed into the system before the gear change, as by this means heavier forces will be obtained at high speed. However, this would not give any advantage as far as backlash is concerned, except when the backlash is in the linkage to the feel system. If backlash in the control run and power control valve are major control problems and cannot be removed

/by redesign..

by redesign, then it is necessary to fit the variable gearing on the output side of the power control. In this case for satisfactory control force variation with speed, a more complicated feel system with force proportional to some function of speed would probably be necessary.

With the gear change under the control of the pilot, there would be the further advantage that he could select different gearings for different operational tasks and atmospheric conditions. It might also be possible to reduce forces in the manual reversion case. On these grounds and also for it's simplicity, a system under the control of the pilot is preferred to one controlled by undercarriage or flap operation, excepting when the former would lead to unacceptable hazards.

Care would, however, be necessary to ensure that with any gearing selected, the risks of overstressing the aircraft were not excessive, either by ensuring that the normal force requirements are met in any gearing or by the provision of visual accelerometers, 'g' restrictors or control surface stops.

It is probable that by combining a small measure of non-linearity with a small range of pilot controlled variable gearing, it would be possible to overcome most of the problems likely to arise for some time to come and in cases of difficulty this would seem to be the most promising line to investigate.

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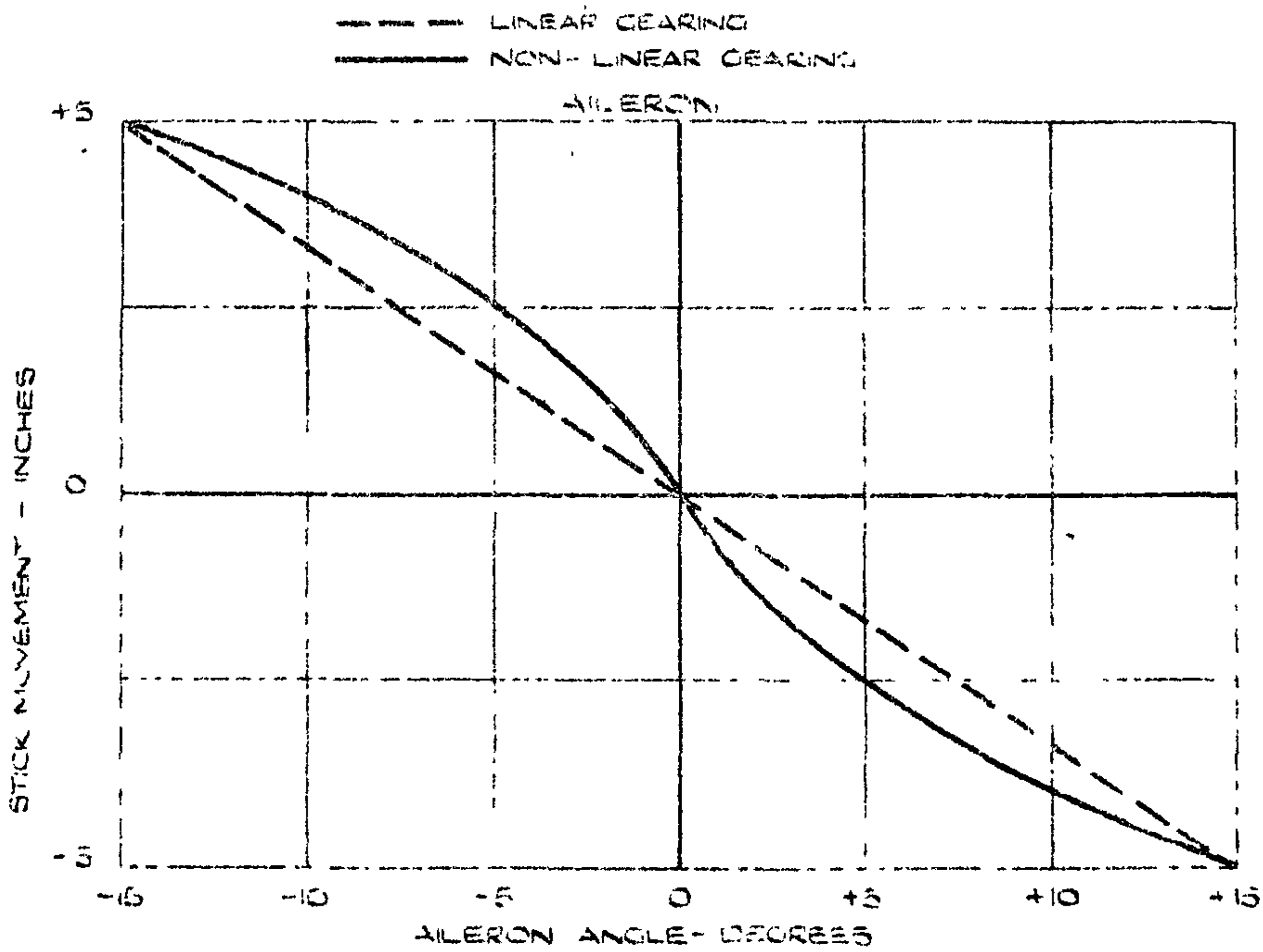
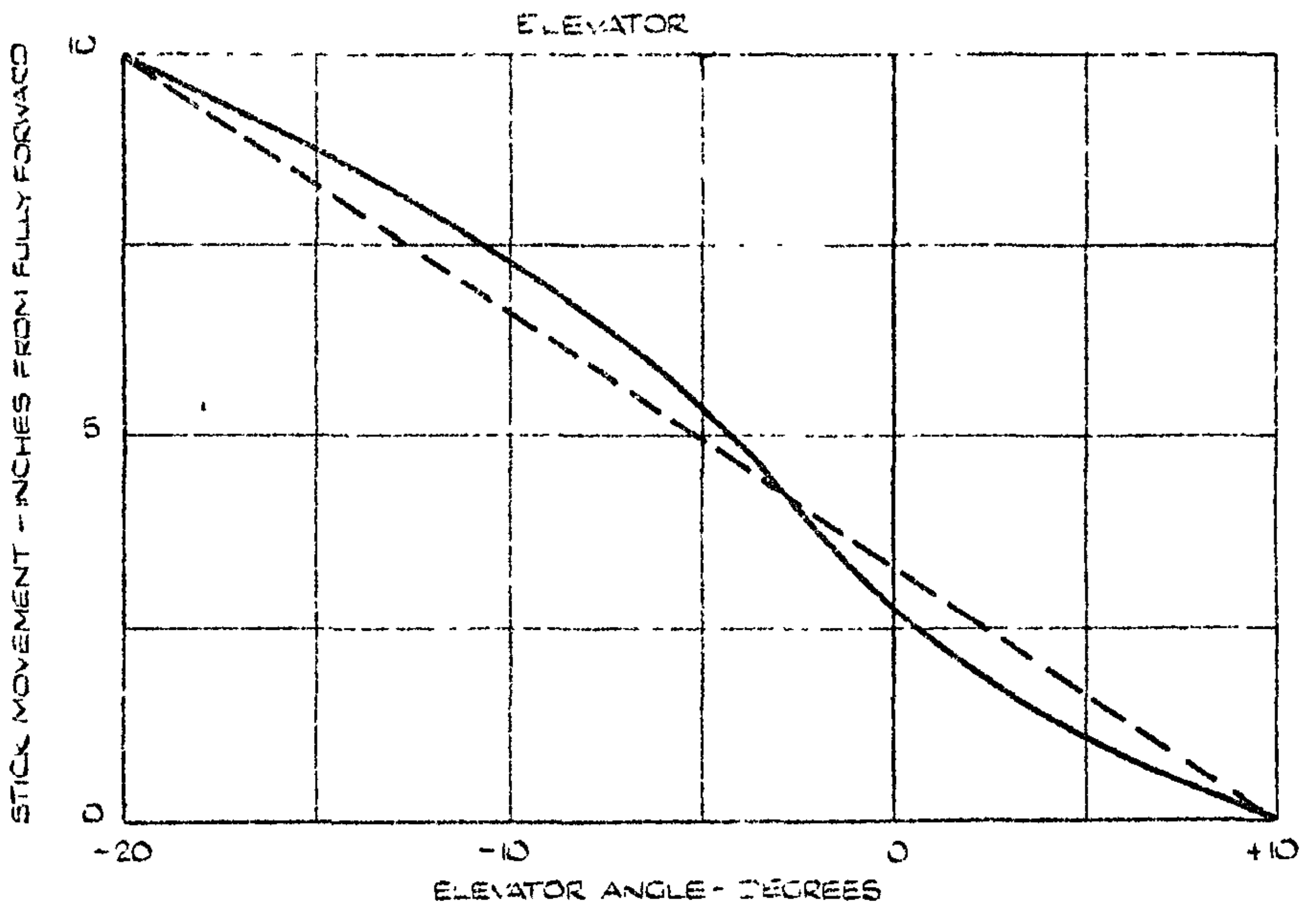
2.	AAEE/Tech/105	D. A. Lang.	Control system requirements for military aircraft in relation to the task of the human operator. A,R.C. 16,968. 26th July, 1954.

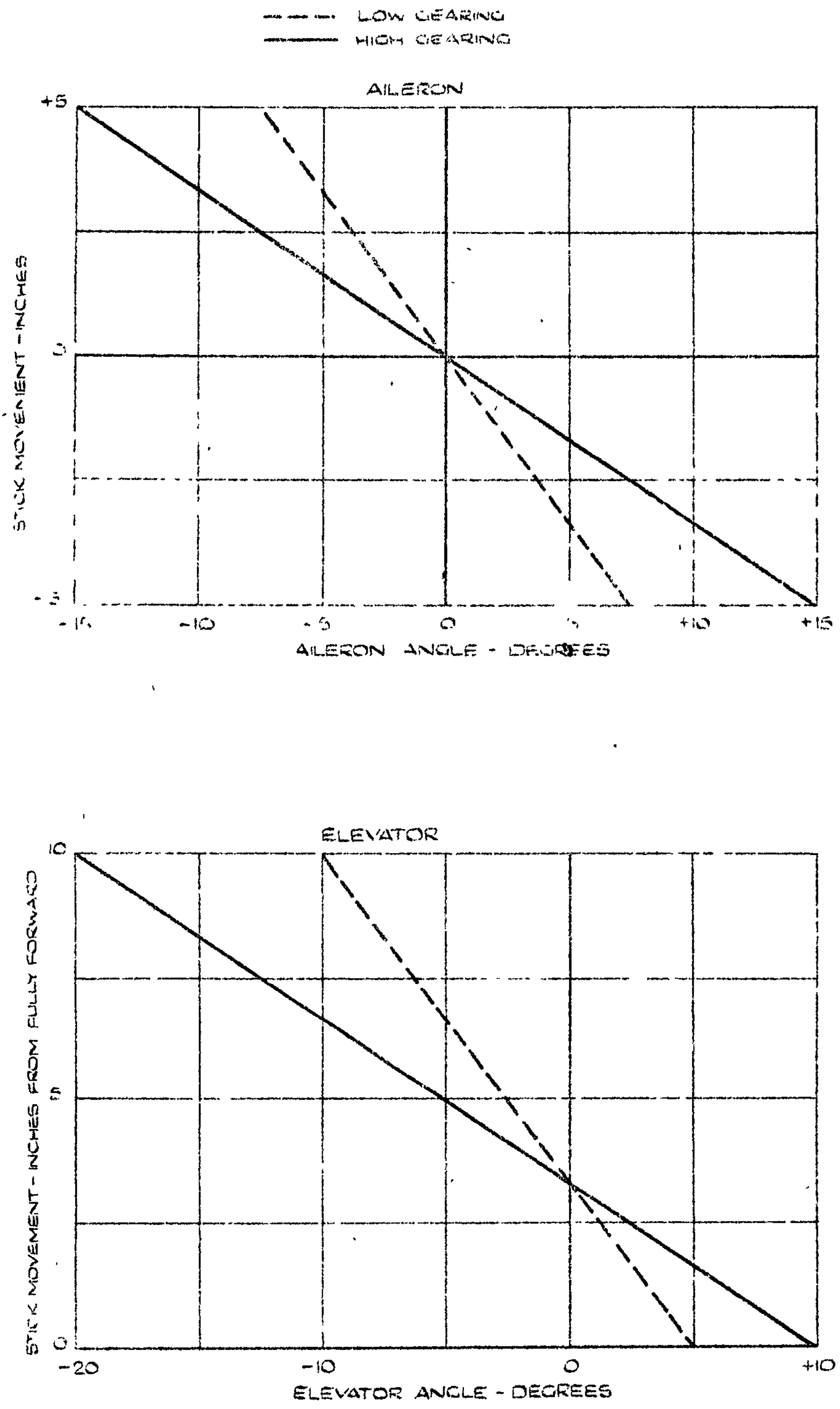
FIG. I.





EXAMPLES OF NON-LINEAR GEARING.

FIG. 2.



EXAMPLE OF LINEAR GEARING.

CONTROL FORCES WITH NON-LINEAR AND VARIABLE GEARING - MANUAL CONTROL.

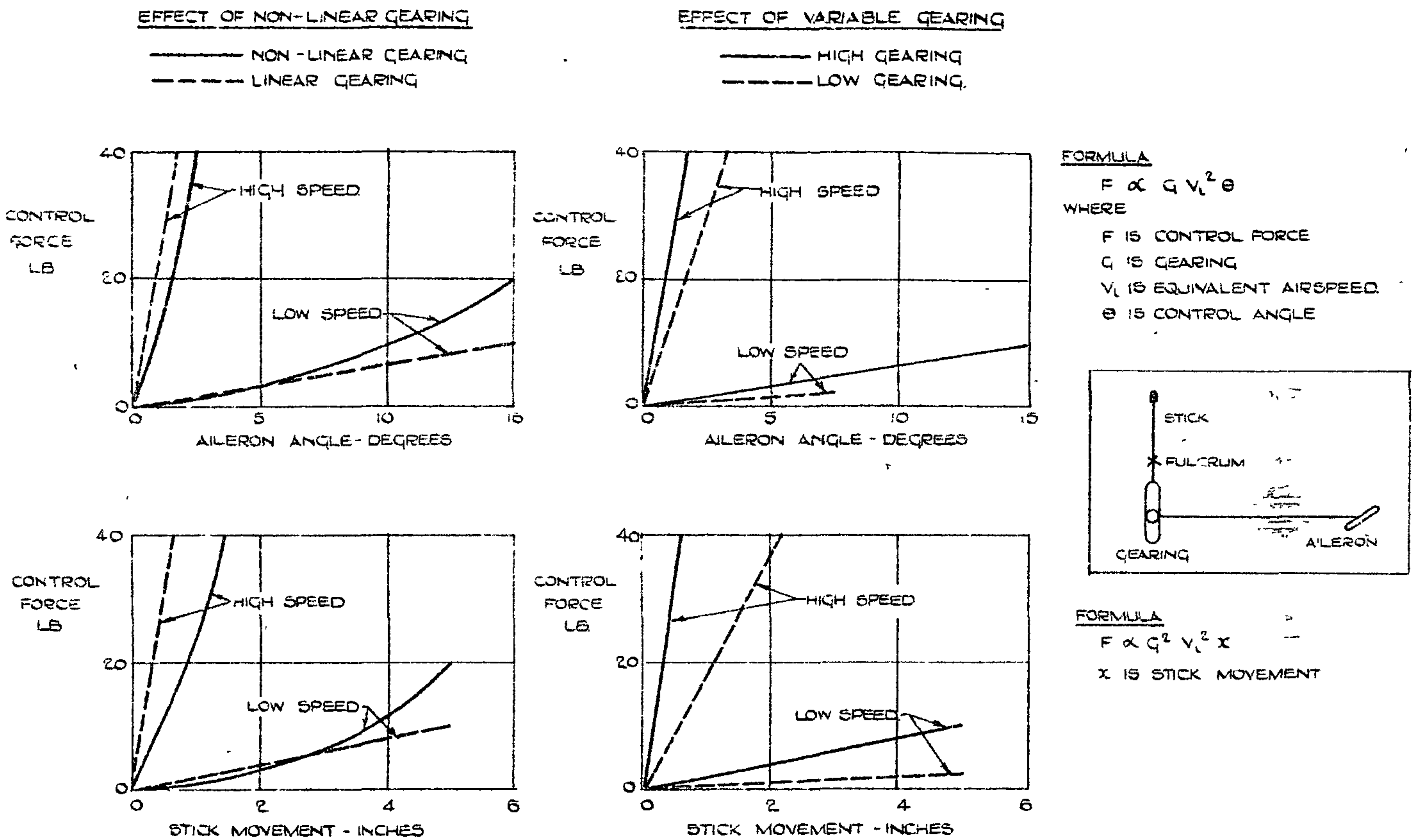
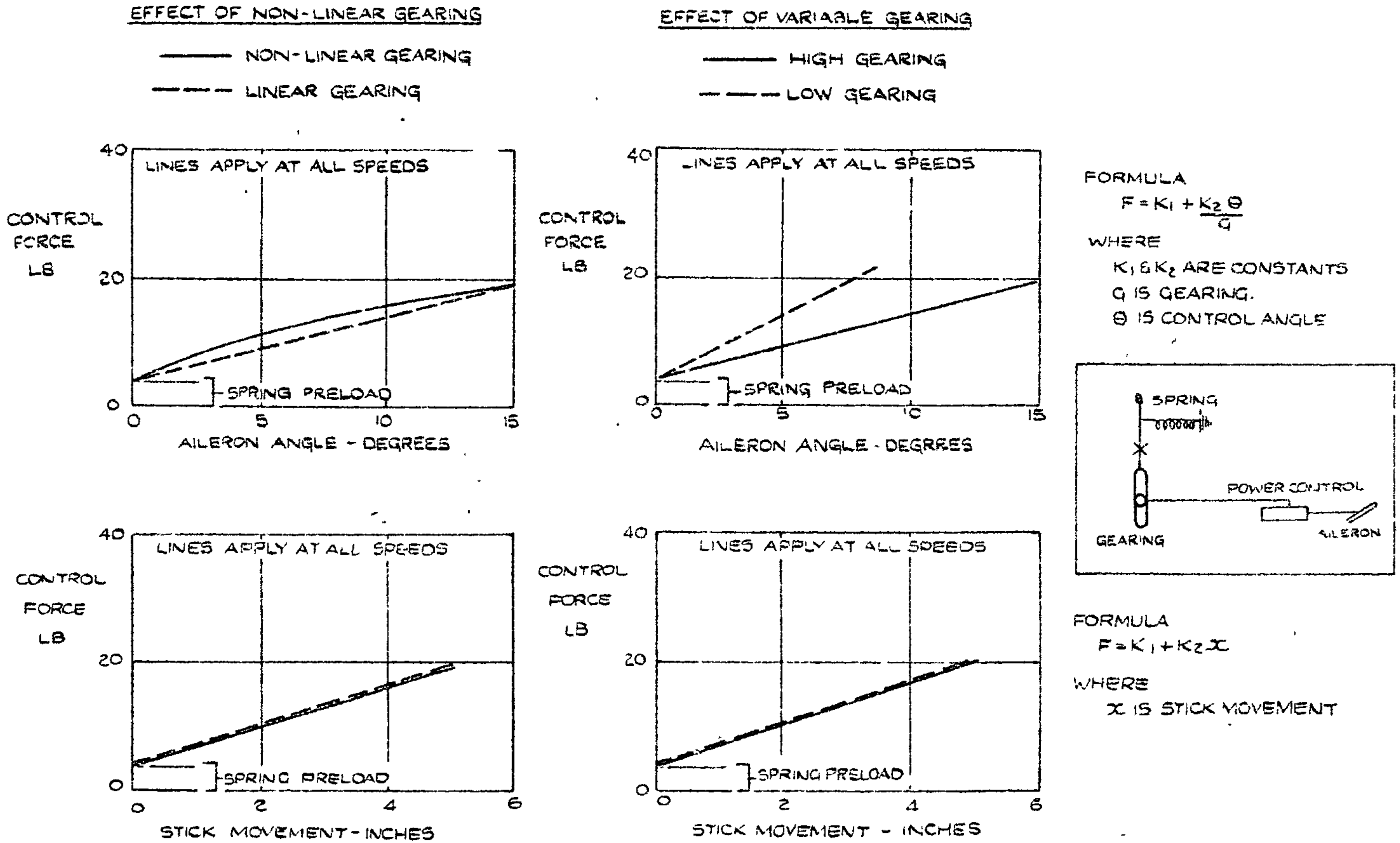
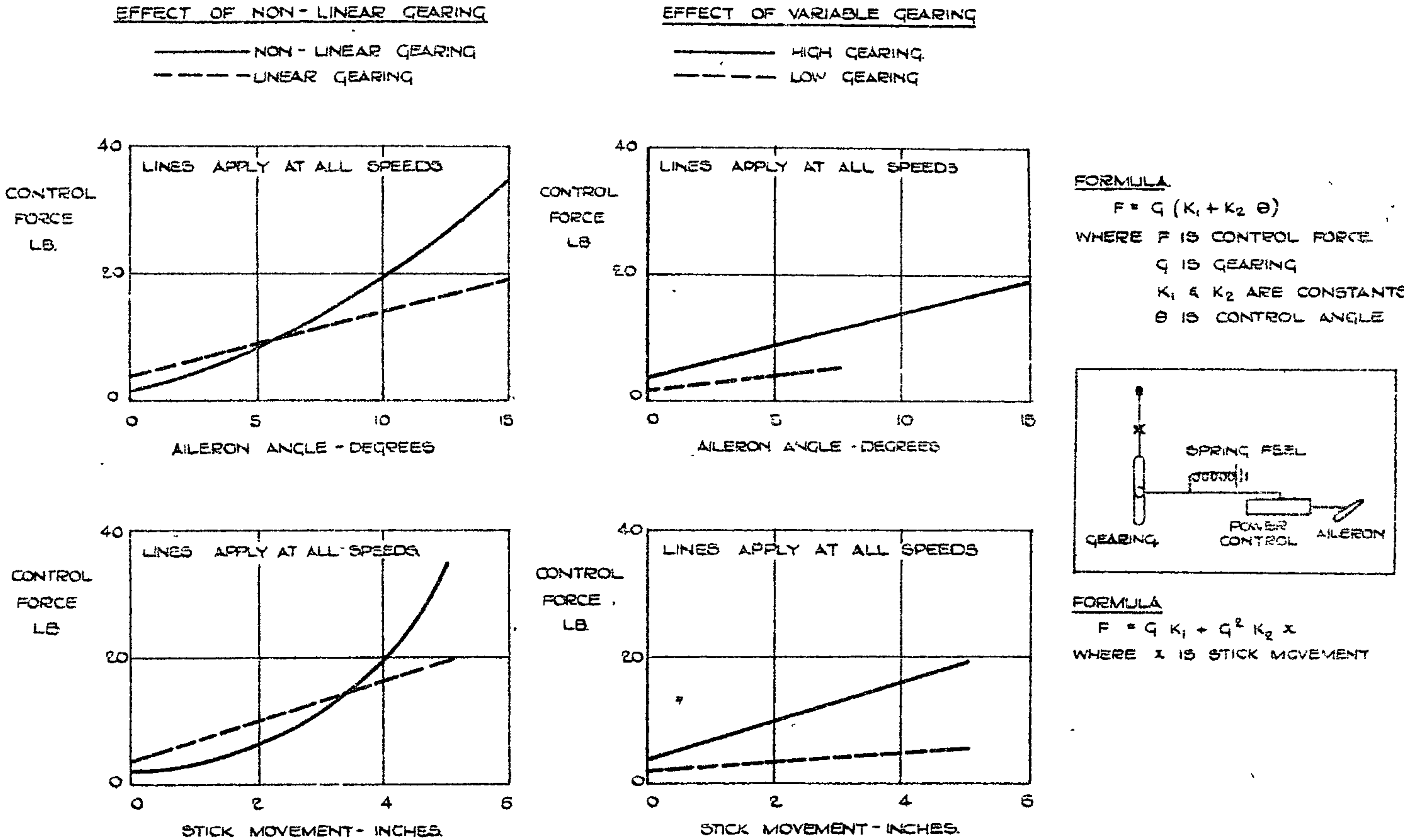


FIG. 3.



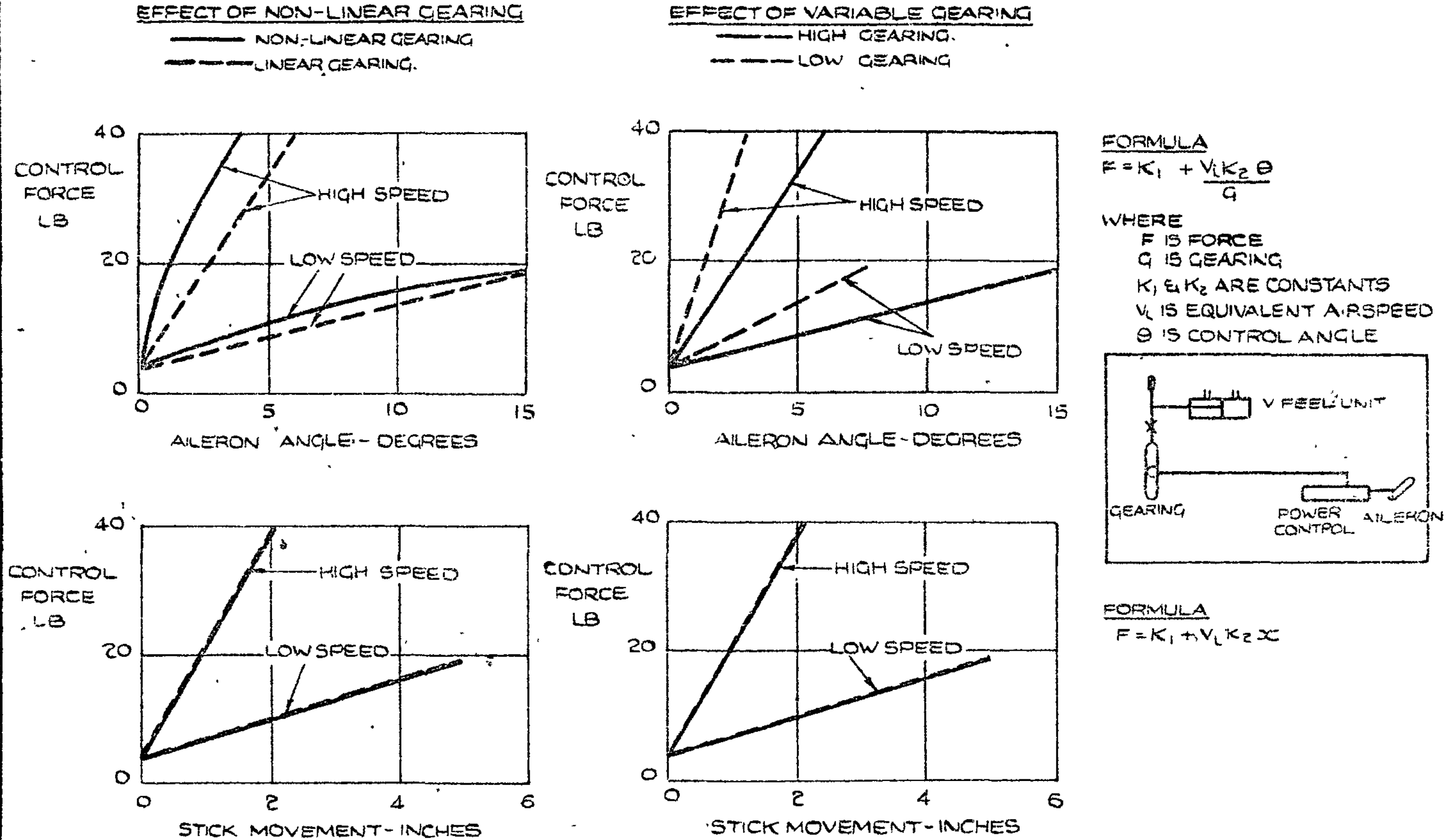
CONTROL FORCES WITH NON-LINEAR & VARIABLE GEARING. POWER OPERATION.
SIMPLE SPRING WITH PRELOAD ATTACHED TO STICK.

FIG. 4.



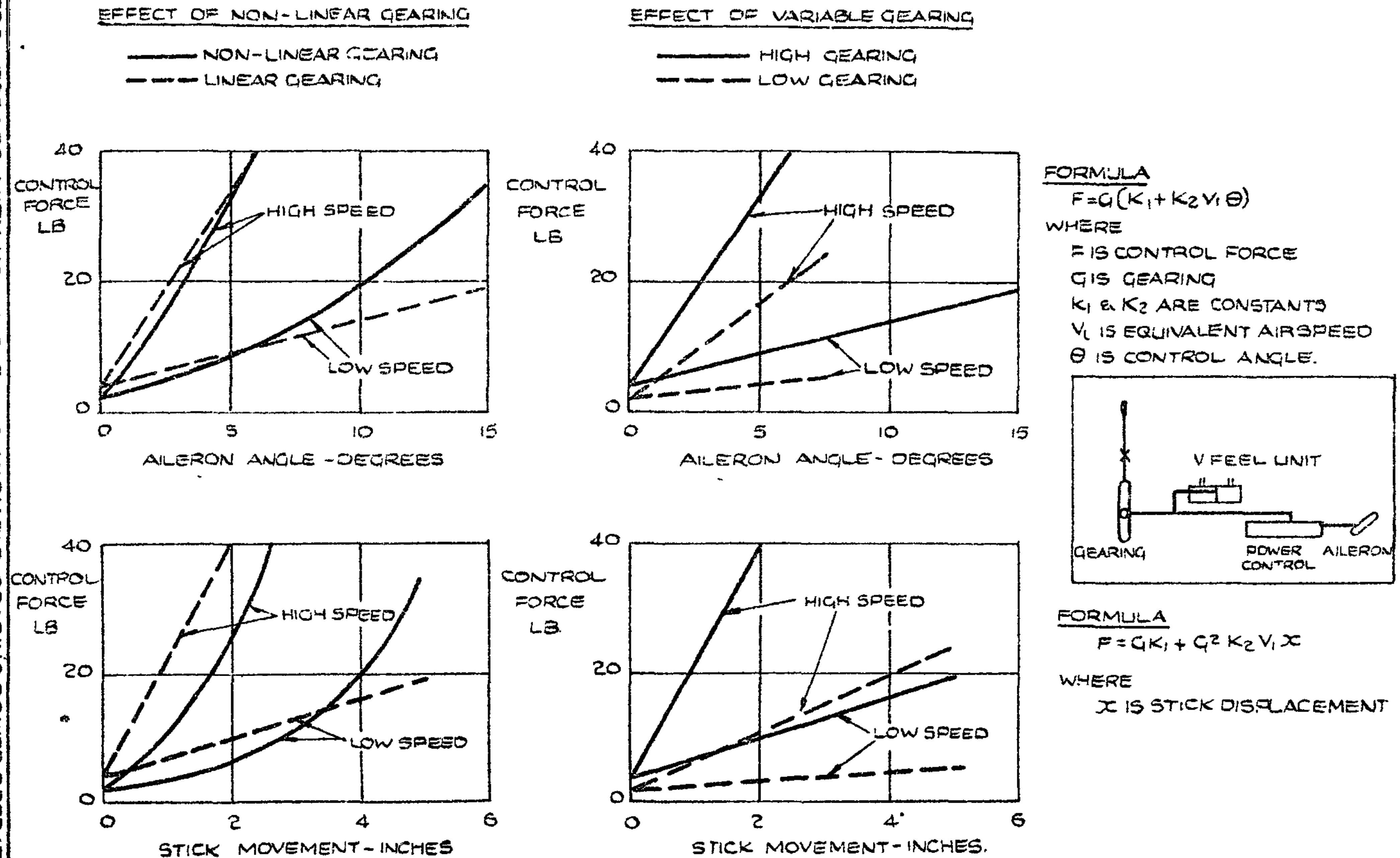
CONTROL FORCE WITH NON-LINEAR AND VARIABLE GEARING. POWER OPERATION. SIMPLE SPRING ATTACHED AFTER GEARING.

FIG. 5.



CONTROL FORCES WITH NON-LINEAR AND VARIABLE GEARING. POWER OPERATION. FORCE PROPORTIONAL TO V PLUS A CONSTANT CENTERING FORCE FED DIRECT TO STICK.

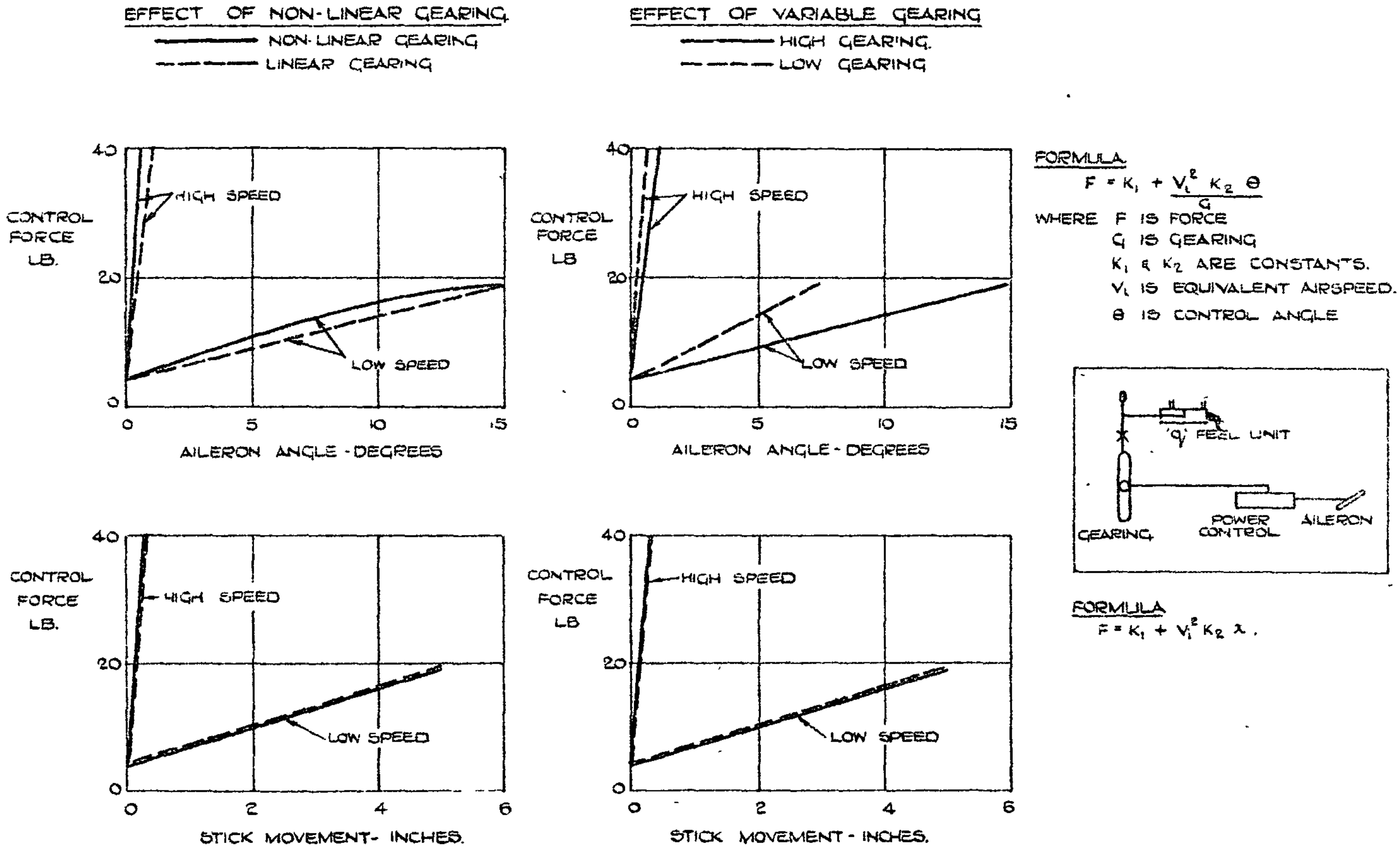
FIG.6.



CONTROL FORCES WITH NON-LINEAR AND VARIABLE GEARING, POWER OPERATION FORCE PROPORTIONAL TO 'V' PLUS A CONSTANT CENTERING FORCE FED IN AFTER GEARING.

FIG.7.

FIG. 8.



CONTROL FORCES WITH NON-LINEAR AND VARIABLE GEARING. POWER OPERATION. FORCE PROPORTIONAL TO V PLUS A CONSTANT CENTERING FORCE FED DIRECT TO STICK.

CONTROL FORCES WITH NON-LINEAR AND VARIABLE GEARING. POWER OPERATION FORCE PROPORTIONAL TO V² PLUS A CONSTANT CENTERING FORCE FED IN AFTER GEARING

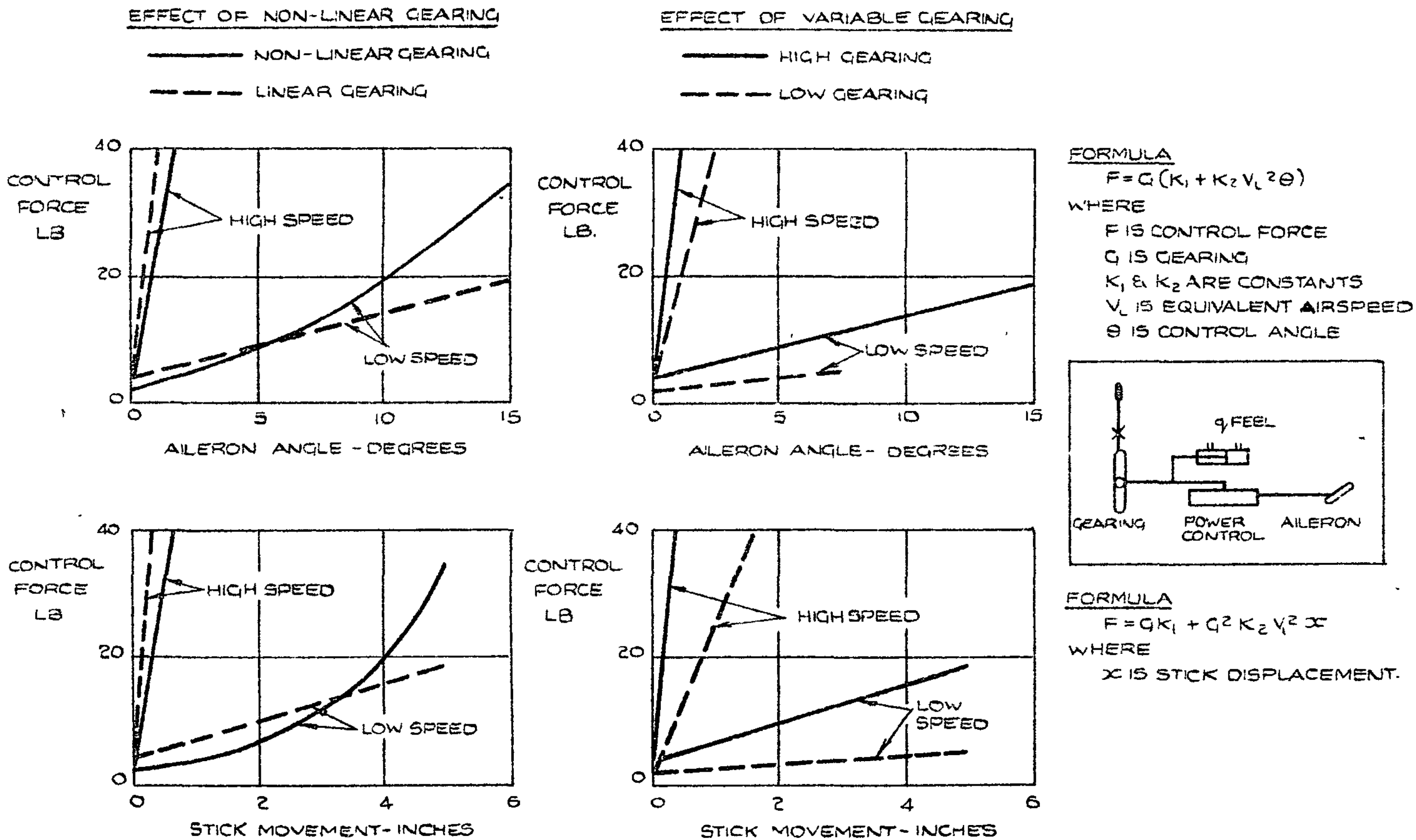
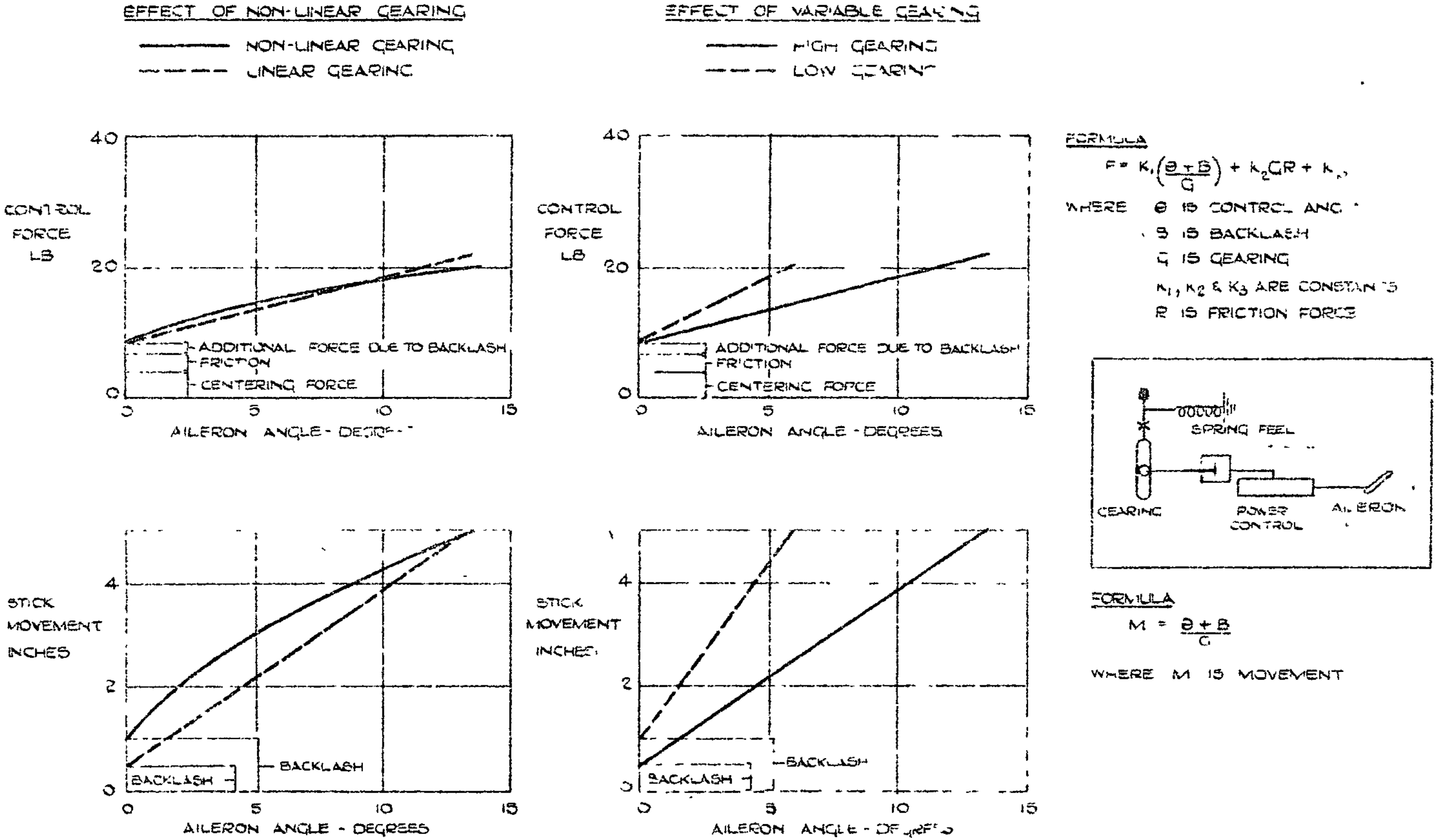
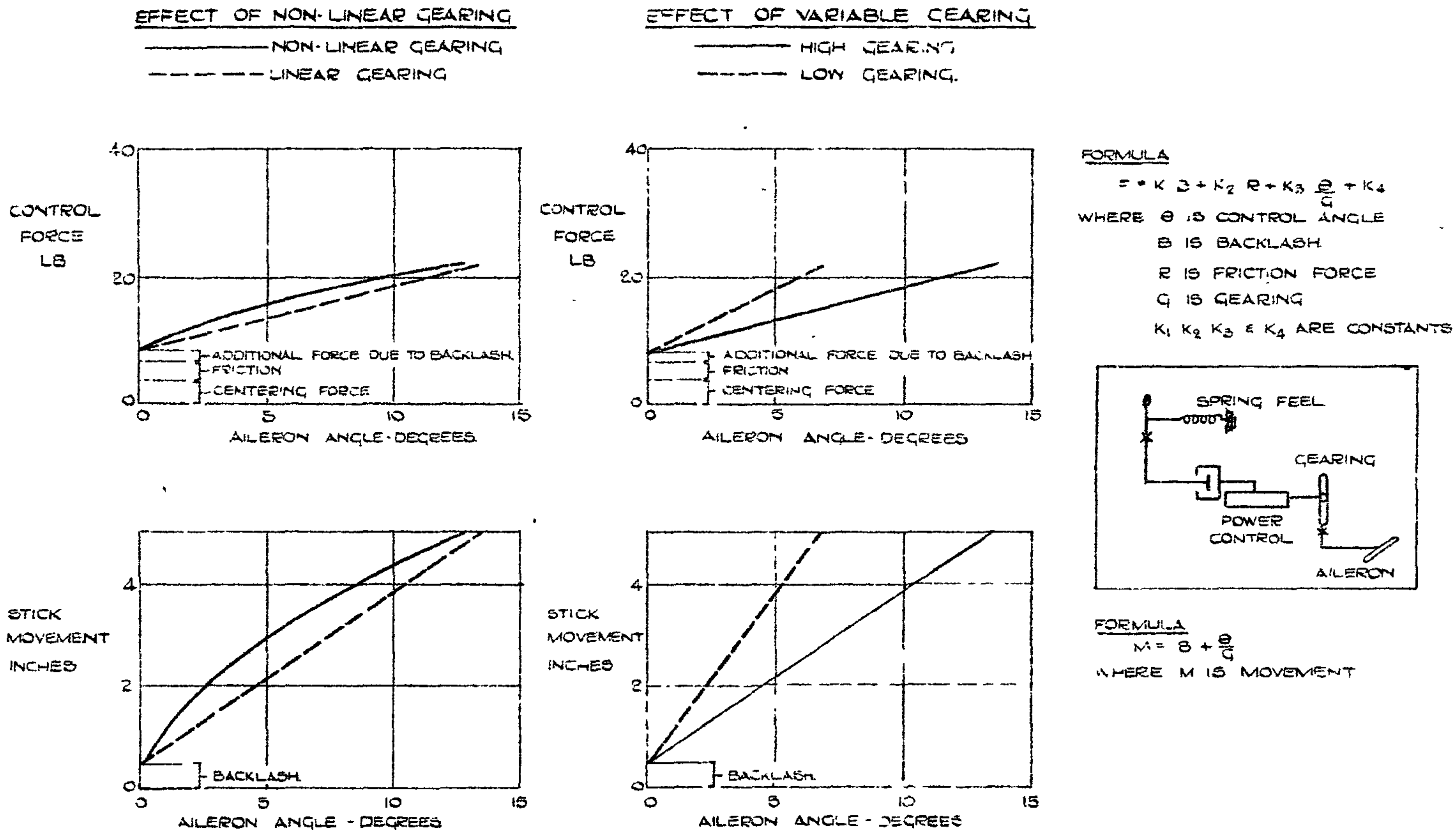


FIG. 9.



EFFECTS OF FRICTION AND BACKLASH WITH NON-LINEAR AND VARIABLE GEARING, POWER OPERATION, SIMPLE SPRING WITH PRELOAD ATTACHED DIRECT TO STICK, GEARING ON INPUT SIDE TO POWER CONTROL.

FIG. 10.



EFFECTS OF FRICTION AND BACKLASH WITH NON-LINEAR AND VARIABLE GEARING. POWER OPERATION. SIMPLE SPRING WITH PRELOAD ATTACHED DIRECT TO STICK. GEARING ON OUTPUT SIDE FROM POWER CONTROL.

FIG. 11.

FIG.12.

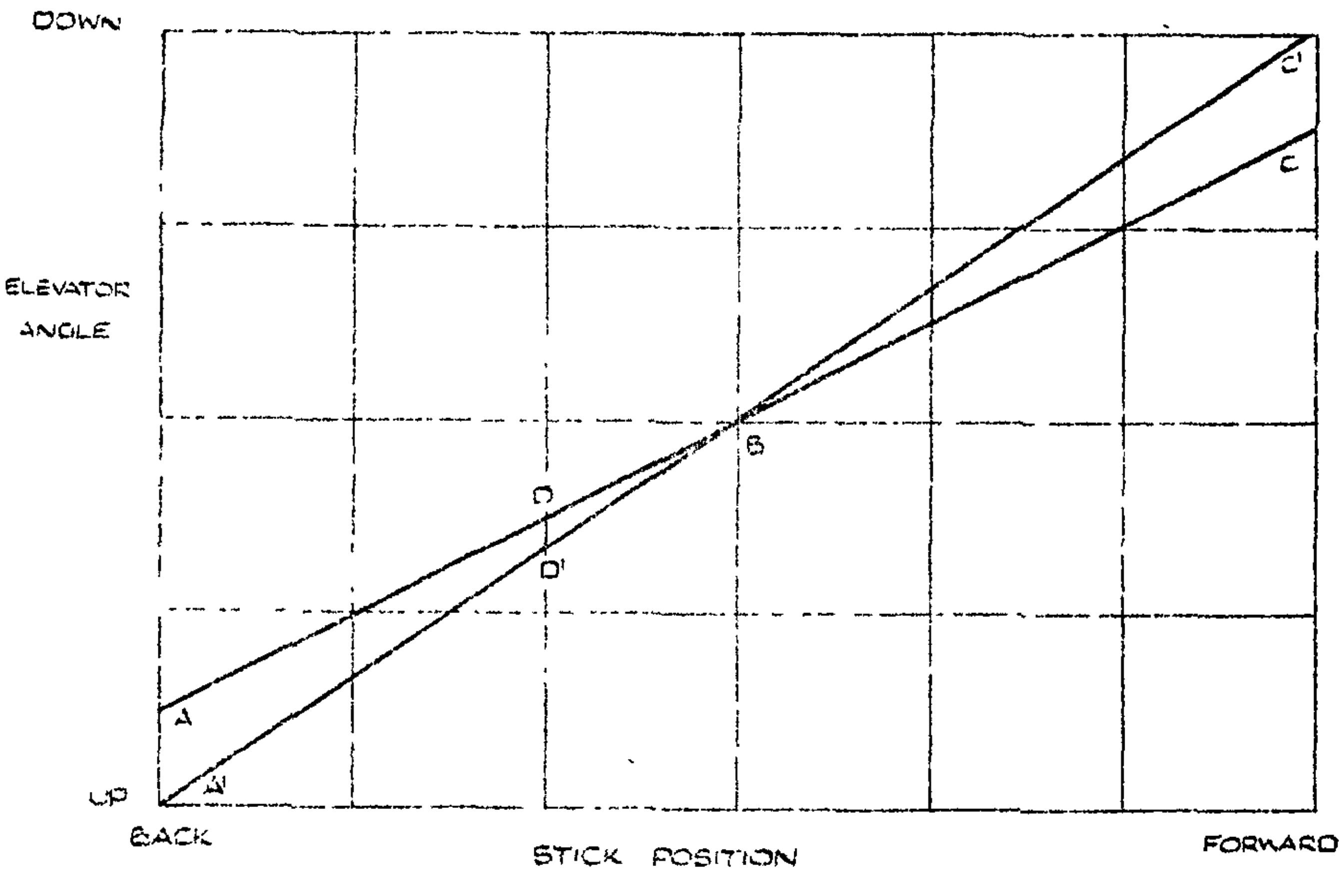


DIAGRAM SHOWING HOW VARIABLE GEARING MAY PRODUCE INSTABILITY.

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