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The Influence of Rolling Moments on Spin Recovery as Observed in Model-Spinning Tests

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Summary.—Several aspects of model-spinning test technique have been brought into prominence by recent full-cale developments. Correlation between model and full-scale recoveries has been poor in some cases, and it appears rom model tests of some new aircraft that full-scale recovery may depend on other means in addition to the normal ise of rudder and elevator.

Analysis of model data shows the effects of applied rolling moments and of aileron deflections on both spin and ecovery to be closely related to the distribution of loading in the aircraft. The ordinary model-test result can be onsiderably in error in either direction due to the neglect of probable scale effects on rolling moments.

Deflection of the ailerons can be of great assistance to model recovery and flight confirmation of this effect is required. nformation on the scale effects on rolling moments for delta aircraft is also urgently needed, as these models show uch greater sensitivity than conventional models to the application of rolling moments.

1. *Introduction.*—Recent trends in the design of fighter aircraft have been in a direction o reduce their ability to recover from spins. New layouts, such as delta and swept-wing plan orms, usually with low aspect ratios and short fuselages, tend to reduce both the damping of otation in yaw and the unshielded rudder area, and at the same time the loadings, particularly he pitching moment of inertia B, are increasing.

As it would considerably prejudice these designs to emphasize unduly the characteristics ecessary to produce good spinning qualities, these tendencies have necessitated (*a*) a more areful investigation into the need for allowing for possible scale effects during free spinning odel tests, and (*b*) examination of the effect of aileron movements in conjunction with the ormal recovery action. These extensions of the model technique help to improve the reliability f the prediction of full-scale characteristics and may reduce the need for drastic modification an aircraft which is not expected to recover by normal use of the controls, if it is found that se of ailerons assists recovery sufficiently to ensure full-scale recovery.

The standard model-spinning test technique[1,2] allows for the presence of scale effect on yawing oments about body axes. Although this is the most important scale effect, Pringle has shown[3] at some models are sensitive to the application of rolling moments and therefore presumably scale effect on rolling moments. It is known that there is a scale effect on rolling moments[4], d a variety of models has been tested in the last few years with additional rolling moments well as additional yawing moments applied.

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This report collects the available model data on the effects of applied rolling moments, and also includes model data on the use of ailerons to assist recovery. A brief mention is made of the general effects on the steady spin but in the great majority of cases the data on the steady spin are too meagre for useful analysis, and the results presented in this paper have been limited to the effects on recovery. The first object of a model-spinning test is, of course, to try to ensure an adequate standard of full-scale recovery.

2. *General Remarks on Rolling-Moment Effects.*—2.1. *Magnitude of Scale Effect.*—Ref. 3 indicates that the order of systematic error in tilt as between model and full-scale spins is equivalent to a difference in rolling moment of about 20 units ($C_l' = 0{\cdot}020$). The model tends to spin with more outwards tilt and thus requires a pro-spin rolling moment to be applied to it as well as a pro-spin yawing moment in order to bring the attitude of the aircraft in the model and full-scale spins into closer agreement.

2.2. *Equivalent Rolling and Yawing Moments.*—An applied rolling moment, δl, changes the tilt of the wings and therefore the sideslip. This change of sideslip produces an additional yawing moment, $\delta_1 n$. From consideration of the simple forms of the rolling and yawing-moment equations during the spin, Ref. 3 shows the ratio of the yawing moment produced to the rolling moment applied to be, at constant incidence :—

$$j = \frac{\delta_1 n}{\delta l} = - \frac{n_v + \dfrac{(A-B)}{\rho S(b/2)^3}\lambda^2 \cos\alpha'}{l_v + \dfrac{(B-C)}{\rho S(b/2)^3}\lambda^2 \sin\alpha'} = -\frac{\nu_v}{\lambda_v} \qquad \ldots \quad (1)$$

where ν_v and λ_v may be termed the total derivatives of directional and lateral stability, including the inertia terms together with the ordinary aerodynamic derivatives n_v and l_v.

Writing K for $\lambda^2 \cos\alpha'/\rho S(b/2)^3$ and approximating $(B - C)$ to $- A$, equation (1) reduces to:—

$$\frac{\delta_1 n}{\delta l} = - \frac{n_v/AK + (1 - B/A)}{l_v/AK - \tan\alpha'} . \qquad \ldots \quad (2)$$

On the average AK is of the order of $0{\cdot}1$ and $\tan\alpha'$ is about $1{\cdot}5$, so that, although the aerodynamic terms do have a secondary effect (provided they are of the same order in the spin as they are below the stall), the sensitivity of a model to the application of rolling moments is largely determined by the distribution of loading. When a pro-spin rolling moment δl is applied and the loading is chiefly in the wings, then $(1 - B/A)$ is positive and the additional yawing moment $\delta_1 n$ is pro-spin, tending to flatten the spin and retard recovery. Similarly, when the weight is chiefly in the fuselage, then $(1 - B/A)$ is negative, $\delta_1 n$ is anti-spin, and the spin is steeper and recovery is easier (*i.e.*, the model will recover against larger yawing moments). As long as l_v remains of its usual sign, that is negative, the direction of the effect cannot change; but it would probably alter if l_v became greater than about $+ 0{\cdot}15$ in the spin.

In the model tests, in order to measure $\delta_1 n$, an extra yawing moment $\delta C_n'$ is applied in the opposite direction until the model spin or recovery behaviour is the same as when no rolling moment $\delta C_l'$ is applied. Thus $\delta C_n' = - \delta_1 n$ and $dC_n'/dC_l' = - j$.

In practice the change in threshold of recovery, $\delta C_n'$, due to an applied rolling moment $\delta C_l'$ is measured. Then if dC_n'/dC_l' is plotted against $(1 - B/A)$ for a number of models, an indication of the average values of the aerodynamic terms n_v and l_v might be obtained, for when $dC_n'/dC_l' = 0$, $n_v = - AK(1 - B/A)$, and by differentiating equation (2), assuming that n_v, AK and α' are constant we get for X, the slope of the curve :—

$$X = \frac{\partial(dC_n'/dC_l')}{\partial(1 - B/A)} = - \frac{\partial j}{\partial(1 - B/A)} = + \frac{1}{l_v/AK - \tan\alpha'} .$$

Therefore $\quad l_v = AK(1/X + \tan\alpha'). \qquad \ldots \quad (3)$

Bearing in mind the assumptions it is unlikely that anything more than a broad value of the aerodynamic terms can be obtained. The model results have therefore been examined with the loading parameter $(1 - B/A)$ as the chief variable.

2.3. *Application of Moments to Model.*—Fig. 1 shows the method of mounting vanes on the wing tips of the model to apply pro-spin yawing and rolling moments. It will be noticed that because the yawing vane is not set at right-angles to the wing chord it also applies a rolling moment in the anti-spin direction. It is assumed that the resultant force on the vane, which is stalled, is normal to its chord (*see* scrap view in Fig. 1). Thus, in the ordinary routine test when no rolling vane is used, the results will in general be in error on account of the equivalent yawing moment produced by this rolling moment. When the loading is chiefly in the wings, this yawing moment is anti-spin (section 2.2) and a larger applied yawing moment is required to obtain the same spin and recovery characteristics as would be obtained if a pure yawing moment only were being applied. Consequently the threshold of recovery in terms of applied yawing moment is optimistically high ; similarly when the loading is chiefly in the fuselage the result is pessimistic.

The net applied rolling moment, C_l', applied by the two vanes is the sum of the moment from the roll vane, C_l'', and the rolling component, $-C_n'$ tan 40 deg, of the moment applied by the yaw vane. Thus

$$C_l' = C_l'' - C_n' \tan 40 \text{ deg.} \qquad (4)$$

These moments are calculated on the basis of the conditions in the steady spin and they vary in recovery, probably not in a similar manner, the yawing moment increasing somewhat and the rolling moment (and its yawing effect) decreasing fairly rapidly as the incidence is reduced. Thus it is to be expected that the ratio j (based on steady-spin measurements of the applied moments) would differ from that apparently obtained in recovery ; the steady-spin value would in fact be the larger. This tendency was demonstrated in tests on the *Wellesley* model, reported in Ref. 3. It is thus possible that the average allowance of 20 units of applied rolling moment, while bringing the model and full-scale steady spins into agreement, may be insufficient to bring the recoveries into complete agreement.

3. *Model Conditions and Methods of Test.*—3.1. *Model Loadings.*—In all cases the original test results have been referred to in order to obtain the exact values of A and B for the models tested. To increase the accuracy still further allowance was made for the contribution of the spike(s) and vane(s) to the rolling moment of inertia. This is discussed in more detail in the appendix. Thus the values of $(1 - B/A)$ quoted may vary slightly from those calculated using the rounded values given in the various model test reports.

3.2. *Control Positions.*—In all the cases considered in this paper the rudder and elevator were fully deflected in the pro-spin direction for the spin and were fully reversed for recovery, either simultaneously or with a very short delay between the rudder and elevator movements. The ailerons were central throughout the tests with applied rolling moments.

For the tests with aileron applied, a variety of aileron positions was used. When the ailerons were central during the spin they were moved pro-spin (stick right in a right-hand spin) or anti-spin simultaneously with the other control movements for recovery. In a number of cases, however, the ailerons were fixed either pro-spin or anti-spin throughout the spin and recovery.

3.3. *Methods of Test with Applied Rolling Moments.*—Usually, the threshold of recovery, in terms of the applied yawing moment, was measured for each of a number of vanes applying pro-spin rolling moments, C_l''. In some cases the rolling-vane size was varied with that of the yawing vane, and these results give only one threshold with a rolling moment C_l'' applied in addition to the threshold measured with yawing vanes only in use. In a few cases, only the effect of applied rolling moment on the time of recovery with a fixed yawing moment applied was measured and the results from these tests are only very rough.

In the analysis, the net applied rolling moment $C_l' = C_l'' - C_n' \tan 40$ deg has been calculated in each case, and the threshold C_n' plotted against C_l'. Fig. 2 shows diagrammatically the types of result obtained. The mean slope of the curve, dC_n'/dC_l', was then obtained in the range $C_l' = - C_n' \tan 40$ deg to $C_l' = 20$ units.

3.4. *Methods of Test with Aileron Deflections.*—The change in threshold of recovery, $\Delta C_n'$, due to deflection of the ailerons was measured for full aileron deflections in pro-spin and anti-spin directions. In the analysis, the rolling power, R, of the ailerons has been estimated by the method of Ref. 5, and $\Delta C_n'/R$ is then a function similar to dC_n'/dC_l' if the other effects of aileron deflections are of minor importance. In the estimation of R, which strictly only applies below the stall, it has been assumed that the control gap was sealed and that there was no balance, which is true for the model ailerons on account of the method of construction.

4. *Results of Analysis of Model Tests.*—Table 1 lists the models tested and gives the results of the analysis of the effects of applied rolling moments and aileron displacements on recovery. The results of the calculations on the inertia of the spike and vane are also given and corrected values of $(1 - B/A)$ are obtained for both sets of tests.

4.1. *Effects of Applied Rolling Moments.*—4.1.1. *The steady spin.*—Reference to the reports containing the original model-test results shows, as predicted in section 2.2, that the application of pro-spin roll does steepen or flatten the spin broadly according to whether or not B is greater than A. The results on the steady spins only give this general indication and, except in the case of the *Wellesley*[3], are not sufficient for any further analysis.

4.1.2. *Recovery.*—For recovery, however, the rate of change of recovery threshold with applied rolling moment, dC_n'/dC_l' has been measured for twenty models, some in more than one loading condition, and this measure of the sensitivity of the models to the application of rolling moments has been plotted in Fig. 4 against the loading parameter $(1 - B/A)$ corrected for the inertia of two spikes and vanes.

Although there is a certain amount of scatter of the experimental points, the results are seen to agree broadly with the prediction of section 2.2 that the recovery is improved ($\delta C_n'$ positive) by the application of pro-spin roll when B is considerably greater than A, and *vice versa*. A mean curve has been drawn through all the points, except those for the two delta models.

Bearing in mind that the values of

(*a*) AK vary between $0 \cdot 03$ and $0 \cdot 4$ } approximately
(*b*) $\tan \alpha'$ vary between $0 \cdot 9$ and $3 \cdot 7$ }

and the possibility of variations of l_v and n_v in the spin, it is surprising that the scatter from the mean curve is so small. The inference is that, broadly speaking, the l_v and n_v terms in equation (2) vary little from aircraft to aircraft in the spin condition, although a badly scattered point, such as number 6, may be explained in terms of an unusually large n_v. As the Airspeed A.S.49 (No. 6) had a long and very deep fuselage and a wing of relatively small chord this seems a likely explanation. Inspection shows that the values of AK and $\tan \alpha'$ vary broadly with $(1 - B/A)$ and it seems probable that the variation of these quantities with $(1 - B/A)$ accounts for the actual shape of the curve.

Obtaining mean values of n_v and l_v in the manner suggested in section 2.2, we get $n_v \simeq 0 \cdot 035$ and $l_v \simeq - 0 \cdot 15$; these values appear sensible in comparison with the few values measured at spin incidences[3].

The two points representing delta aircraft are too far from the curve to be classed as badly scattered points and have been combined to indicate another curve for delta aircraft. Taking average values again, it is found in this case that n_v is zero and l_v is positive, approximately $+ 0 \cdot 07$. The result of a very small n_v is to be expected since practically all the fin surface is immediately above the wing and therefore in its wake, which probably makes the fin totally ineffective. The positive value of l_v, although most unusual in conventional aircraft, is in agreement with the observed trend of l_v to become positive at the stall[6] on delta aircraft and indicates a fundamental difference in the behaviour of these types. This difference may be partly a result of the very high taper of the wings.

4.2. *Effects of Aileron Deflections*.—4.2.1. *The steady spin*.—Once again, the measurements of the effects of having the ailerons deflected in the steady spin are insufficient to permit any quantitative analysis. They do, however, indicate that ailerons deflected in say the pro-spin sense, *i.e.*, left aileron up in a left-hand spin and *vice versa*, have an effect on the spin, qualitatively similar to that of pro-spin applied rolling moment, which depends chiefly on the sign of $(A - B)$. Pro-spin aileron deflections cause the spin to be steeper or flatter depending chiefly on whether or not B exceeds A.

4.2.2. *Recovery*.—Thirteen models have been tested with the ailerons deflected. There is some slight evidence (Table 1, Models 16, 20, 21, 22) that the effect on recovery was greater when the ailerons were deflected throughout spin and recovery rather than during recovery only (for the same direction of spin).

Fig. 5 shows the effect of aileron deflections on recovery threshold, $\Delta C_n'$, related to the estimated rolling power, R, of the ailerons plotted against $(1 - B/A)$ corrected for the inertia of one spike and vane. The points fall into three distinct groups :—

(*a*) conventional aircraft, and tailless aircraft on which down elevon angles in the ' elevator ' sense were limited to small values

(*b*) delta aircraft

(*c*) tailless aircraft on which the ' aileron ' angles were superimposed on large down ' elevator ' angles.

Besides the causes of scatter operating in the case of the tests with rolling moments (section 4.1.2) there is an additional cause in this case due to the inaccuracy of the estimation of aileron power, R, in the stalled condition. Also no allowance has been made for the direct yawing moments produced by the aileron deflections. These extra effects do not appear to be of importance as far as the general shape of the curve is concerned for the scatter is no worse than in Fig. 4, but in an individual case such as Model 16, the point is above the line in Fig. 4 and below it in Fig. 5, indicating a considerably reduced rolling moment from the ailerons compared with the estimation.

Curve I for conventional and some tailless aircraft is very similar in shape to the curve for conventional aircraft in Fig. 4 and the axis of $(1 - B/A)$ is again crossed at $- 0 \cdot 37$, confirming the previous estimate of an average value of n_v. It also agrees qualitatively with some American data[7] on aileron effects, where it was found that the direction of the effect reversed at a value of $(A - B)/mb^2$ of $- 0 \cdot 005$ approximately, the average $(B - C)/mb^2$ during these tests was about $- 0 \cdot 010$ so that $(1 - B/A) = - 0 \cdot 5$ approximately.

Comparison of Curve I with the curve for conventional aircraft in Fig. 4 indicates that the rolling power of the ailerons is on the average about $0 \cdot 8$ times that estimated for low incidences, although in the case of Model 16 for instance it appears to be about only $0 \cdot 3$ times.

In the case of delta aircraft, however (Curve II), although the points lie well away from those for conventional aircraft, as in Fig. 4, (again an n_v of zero is indicated) the slope of the line is much reduced in comparison with that of the curve for delta aircraft in Fig. 4. Comparing the two slopes indicates that the rolling power of the ailerons is of the order of 0·15 times that estimated. This very large difference may be a direct result of the extremely high taper ratios of these aircraft combined with low aspect ratios.

The points for tailless aircraft fall into two groups. The explanation of this is thought to lie in the extent of the elevon movements. In the case of the models included in Curve I the elevons had a fairly small limiting downwards angle in each case even though they were being used as 'elevators' as well as 'ailerons'. In the case of Curve III, however, large 'aileron' angles were superimposed on large down 'elevator' angles so that in recovery with the stick fully forward and to one side one elevon was fully deflected downwards and the other was more or less undeflected. This would give rise to a large anti-spin yawing moment when the 'ailerons' were pro-spin for recovery (and *vice versa*) which would tend to improve recovery irrespective of the rolling effect and the sign of $(A - B)$. Thus the points (Curve III) are displaced upwards, *i.e.*, recovery is improved with pro-spin 'aileron' deflections relative to the points (Curve I) where the 'ailerons' were deflected approximately uniformly on either wing.

The similarity of the curves of the effects of applied rolling moment and of aileron deflections (Figs. 4 and 5) for conventional aircraft suggests that the direct yawing moment from the ailerons is of minor importance. In the case of some tailless aircraft this is not so, as explained above.

5. *General Discussion.*—Several aspects of spinning are affected by the results of the analysis presented in the previous section. They are discussed in some detail below.

5.1. *Model Test Technique.*—It is clear from the collection of model evidence presented in Fig. 4 that the normal yawing-vane technique can lead to predictions of full-scale recovery which can be considerably in error in either direction, depending on the distribution of loading in the aircraft. The range of loading distributions now in use is so wide, the practical values of $(1 - B/A)$ range from -2 to $+\frac{1}{2}$, that it is felt that the model test programme should always include a brief check of the effect of applied pro-spin rolling moments. In the absence of better information on the scale effects on rolling moment, that given in Ref. 4 should be accepted; that is, a pro-spin rolling moment of 20 units net should be applied to the model.

To avoid complication in the comparison of model and full-scale behaviour it is suggested that in future the rolling moment of inertia of the model should be less than the scale value by an amount, in slug/ft^2 $\times$ 10^{-5}, of $2b^3$ in routine tests and $4b^3$ in tests with rolling moments applied, where b is the model span in feet, to allow for the inertia of the spikes and vanes.

5.2. *Standard of Recovery.*—The standard of recovery at present required as set out in Ref. 3 includes an allowance for the effects of applied rolling moments. At that time, however, only a few models had been tested with rolling moments applied, and the correction was necessarily crude. It would be of great interest and value if the curve of Fig. 4 were used to correct the thresholds of recovery of the models used in Ref. 4 where no measurement of the effect of rolling moments exists; it might be possible in this way to revise the standard of recovery required. At the same time, later cases of full-scale–model comparisons, of which there is a number, could be included. This revision might cause some modification to the standard but it should certainly help to improve the separation of passes and failures.

There is also the effect of the error in A due to the inertia of the spike and vane to be allowed for, as this is one of the causes of scatter which can be removed.

5.3. *Swept-back Tailless and Delta Aircraft.*—No full-scale–model comparisons based on the vane technique exist for these aircraft. The present results indicate the urgent need for such a comparison. Although no models of tailless aircraft have been tested with rolling moments applied, it appears from the tests with 'ailerons' deflected (Fig. 5) that they may be fairly sensitive to this effect. Ref. 8 confirms this sensitivity to 'aileron' deflection in one full-scale case. In view of this and of the great sensitivity of delta models to the application of rolling moments, it is obviously of great importance that some indication of the order of scale effect on rolling moment as well as on yawing moment should be obtained as soon as possible either by flight-model comparisons or by rolling balance tests. Otherwise the prediction from model results of the probable full-scale behaviour is practically impossible for both these types of aircraft.

5.4. *Recovery Technique.*—Table 1 and Fig. 5 indicate that for aircraft with the loading chiefly in the fuselage, in which direction present-day aircraft are tending, the use of pro-spin aileron deflections is distinctly beneficial to recovery. In some cases improvements in recovery of over 10 units of applied yawing moment have been measured. No recent confirmation of the effectiveness of the ailerons in spin recovery full-scale exists, and the need for comparative tests on a suitable aircraft is self-evident.

On an aircraft on which the effectiveness of the aileron control in helping the recovery from a spin is large, it is unlikely that we can afford to neglect its use, especially if the normal recovery is poor. There are obvious dangers that must be overcome, however, for the possibility of wrong application of aileron is present, and it remains to be seen how effectively pilots could be drilled to use a new technique of spin recovery which could vary from aircraft to aircraft in a vital particular.

6. *Conclusions.*—(*a*) This collection of model data on spin recovery shows that the scale effect on rolling moments is important. By its neglect, an error may arise in the interpretation of model test results.

This error may be in either direction and is largely dependent on the distribution of mass in the aircraft. Thus if the ratio of pitching to rolling moments of inertia is considerably more than unity, the model result is pessimistic; if less than unity the model result is optimistic.

Sufficient model data on the effect of applied rolling moments now exist to allow a revision of the routine model standard of recovery using the previous model–full-scale comparisons of R. & M. 1967[3]. It is also proposed that future model tests should always include a brief check on this effect in order to increase the reliability of the prediction of full-scale characteristics.

(*b*) The effects of aileron deflections on conventional aircraft are due primarily to the rolling moments they apply, and are similar qualitatively to those of applied rolling moments. The direct yawing effect is of minor importance except in the special case of tailless aircraft on which large 'aileron' angles are superimposed upon large down 'elevator' angles, which results in one elevon being far down and the other practically undeflected. In this case the yawing moments are important.

(*c*) Delta models are much more sensitive to the application of rolling moment than conventional models, and it is of great importance that information on the probable order of scale effects on such types, and also on tailless types, should be obtained as soon as possible.

(*d*) Full-scale information is also required on the effectiveness of aileron deflections in aiding spin recovery, in order to provide a comparison with the model results, which indicate that use of ailerons can, in certain circumstances, powerfully aid recovery.

(*e*) An error in the rolling moment of inertia, inherent in the method of test, due to the weight of the spikes and vanes used to apply the moments to the model, has been investigated. The increase, ΔA in slug/ft^2 $\times 10^{-5}$, in the inertia due to a spike and vane is approximately equal to $2b^3$ where b is the model span in feet. Corrections have been made to all the loadings used in this report, and as it is a potential cause of scatter, all future collections of model data and model–full-scale comparisons should take it into account.

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APPENDIX

Error in Rolling Moment of Inertia due to Weight of Spike and Vane

It was noticed in obtaining the values of A and B that some early models had small rolling moments of inertia, A, in relation to the wing span. A few rough estimates were made of the effect on A of the weight of the spike and vane attached to the wing tip. It was found that the extra rolling moment of inertia for one spike and vane could be over 20 per cent of the correct scale value of A and in fact for Model 4 (Table 1) A was in error by over 40 per cent when tests were done with both rolling and yawing moments applied. Since the moments of inertia of the models are always measured without the spike and vane being attached, this represents a considerable error in the conditions of the model test. The contribution ΔA of the spike and vane was therefore calculated for every model included in this report. An average vane size was chosen for each model. The results of the calculations are given in Table 1 and are plotted against b^3 in Fig. 3, where b is the model span in feet. ΔA is proportional to b^3 as would be expected, as the length of the spike and size of the vane are both roughly proportional to b as are their distances from the c.g. The actual result is $\Delta A = 2b^3$, in slug/ft^2 $\times$ 10^{-5}.

The scatter of the points is largely due to the fact that all models do not have the same threshold of recovery, *i.e.*, the vane size varies somewhat at a given span for different models. The contribution of the spike alone is also shown in Fig. 3 and it is seen to be the major part of the error.

The values of $(1 - B/A)$ as obtained by swinging the model as a compound pendulum (without the spike and vane attached) have therefore all been corrected for this increase in A. In the case of the rolling-moment tests, two spikes and vanes have been allowed for, and only one in the case of the aileron tests.

As this correction may be so large, it is felt that it should be applied to the loadings whenever any attempt is being made to collect model data for the purpose of predicting full-scale characteristics, *e.g.*, when spinning criteria are being considered.

LIST OF SYMBOLS

A	Rolling	moments of inertia about the principal axes
B	Pitching	moments of inertia about the principal axes
C	Yawing	moments of inertia about the principal axes

ΔA	Contribution of one spike and vane to A
b	Wing span
C_l''	Rolling moment applied by roll vane (body axes)
C_n'	Yawing moment applied by yaw vane (body axes)
C_l'	Net applied rolling moment $= C_l'' - C_n' \tan 40$ deg
$\bar{c}$	Wing mean chord
j	Ratio of equivalent rolling and yawing moments $= - \nu_v/\lambda_v$
K	$= \lambda^2 \cos \alpha'/\rho S(b/2)^3$
l_v	Sideslip derivative of aerodynamic rolling moment (body axes)
m	Aircraft mass
n_v	Sideslip derivative of aerodynamic yawing moment (body axes)
R	Rolling power of ailerons estimated by method of Ref. 5
S	Wing area
V	Rate of descent
α'	Incidence of principal axis of inertia in the fuselage
λ	Spin parameter $= \Omega b/2V$
λ_v	Sideslip derivative of total rolling moment in body axes
ν_v	Sideslip derivative of total yawing moment in body axes
Ω	Angular velocity of spin
ρ	Density

TABLE I.

Model Data on Effect on Spin Recovery of Applied Rolling Moments and of Aileron Deflections

Nº	AIRCRAFT	TYPE	AIRCRAFT DIMENSIONS (FULL SCALE) S SQ FT	b FT	$\bar{c}$ FT	SCALE OF MODEL	b^3 CU. FT M S	ΔA SL.FT.^{2} x 10^{-5} DUE TO ONE SPIKE AND VANE	$(1-\frac{B}{A})$ OF MODEL IN TEST	$\frac{\Delta A}{A}$	$(1-\frac{B}{A})$ CORRECTED FOR $2\times\frac{\Delta A}{A}$	$\frac{dC'_n}{dC'_l}$	$(1-\frac{B}{A})$ OF MODEL IN TEST	$\frac{\Delta A}{A}$	AILERONS (1) DEFLECTED IN SPIN	IN RECOVERY	$\Delta C'_n$ DUE TO AILERONS (UNITS $10^{-3}C'_n$)	AILERON POWER (2) AT FULL DEFLECTION = R (UNITS $10^{-3}C'_l$)	$(1-\frac{B}{A})$ CORRECTED FOR $1\times\frac{\Delta A}{A}$	$\frac{\Delta C'_n}{R}$
(A) CONVENTIONAL AIRCRAFT																				
1	SPITFIRE	FIGHTER	231(3)	33·5	6·90	1/30	1·39	2 1/2	−0·48	0·072	−0·29	−0 02	—	—	—	—	—	—	—	—
2	DEFIANT (4)	NIGHT-FIGHTER	250	39·4	6·35	1/30	2·27	4	−1 68	0·155	−1·05	+0·34	—	—	—	—	—	—	—	—
									−1·56	0·120	−1·06	0·18	—	—	—	—	—	—	—	—
3	BRISTOL 133 (4)	FIGHTER	271	39·0	6·95	1/22	5·57	10	−0·02	0·087	+0·13	−0·03	—	—	—	—	—	—	—	—
									+0·49	0·044	0·53	−0·14	—	—	—	—	—	—	—	—
4	MOTH MINOR (4)	LIGHT A/C	162	36·0	4·50	1/16	11·39	23	−0·20	0·202	0·14	VARIABLE ~0	—	—	—	—	—	—	—	—
5	WELLESLEY (4)	GENERAL PURPOSE	618	73·8	8·38	1/28	18·30	48 1/2+13 1/2(5)	+0·37	0·32(5)	0·52(5)	−0·25	—	—	—	—	—	—	—	—
6	AIRSPEED AS.49	FIGHTER-TRAINER	98·5	25·0	3·94	1/18	2·68	5 1/2	−1·45	0·105	−1·02	0	—	—	—	—	—	—	—	—
7	MAGISTER	TRAINER	179	33 83	5·30	1/16	9·44	17	—	—	—	—	−0·69	0·137	ANTI	ANTI	−3	63 6	−0·49	0·047
8	MILES M.28	TRAINER	160	30·25	5·29	1/12	16·01	34	−1·09	0·079	−0·81	+0·06	—	—	—	—	—	—	—	—
9	BEAUFIGHTER	NIGHT-FIGHTER	503	57·8	8·70	1/32	5·89	12	+0·53	0·041	+0·57	−0·17	—	—	—	—	—	—	—	—
10	TYPHOON	FIGHTER	279	41·58	6·71	1/24	5·20	11 1/2	0·11	0·054	0·20	−0·19	+0·16	0·053	PRO	PRO	−2 1/2	50 0	0·20	−0·050
									—	—	—	—	↓	↓	CENTRAL	ANTI	+4 1/2	↓	↓	−0·090
11	WELKIN	FIGHTER	465	70·0	6·64	1/32	10·47	19	0·45	0·047	0·50	−0·06	0·48	0·075	PRO	PRO	−7	48·0	0·52	−0·146
									—	—	—	—	↓	↓	ANTI	ANTI	+4 1/2	↓	↓	−0·094
12	VICKERS F7/41	FIGHTER	435	56·9	7·65	1/32	5·61	9 1/2	0·35	0·048	0·41	−0·11	—	—	—	—	—	—	—	—
13	G.A. TX3/43	GLIDER-TRAINER	182	35·0	5·20	1/15	12·70	23	−0·55	0·098	−0·29	0	−0·23	0·098	CENTRAL	ANTI	1	57·6	−0·12	−0·017
14	VAMPIRE	FIGHTER	260	40·0	6·50	1/27	3·26	6 1/2	−0·42	0·104	−0·17	~0	—	—	—	—	—	—	—	—
15	METEOR 2	FIGHTER	387	44·33	8·72	1/32	2·66	4 3/4	—	—	—	—	−0·51	0·076	ANTI	ANTI	2	61·6	−0·40	−0·032
16	AEROPLANE 'A'	NAVAL-FIGHTER	358	44·0	8·13	1/32	2·60	4 3/4	−1·09	0·060	−0·87	+0·28	−1·01	0·063	CENTRAL	PRO	4	69 8	−0·89	+0·057
									—	—	—	—	↓	↓	PRO	PRO	6	↓	↓	0·086
									—	—	—	—	↓	↓	CENTRAL	ANTI	−4 1/2	↓	↓	0·065
									—	—	—	—	↓	↓	ANTI	ANTI	−6 1/2	↓	↓	0·093
17	AEROPLANE 'B'	NAVAL-FIGHTER	340	41·0	8·29	1/36	1·47	2 3/4	−2·42	0·098	−1·86	0·72	—	—	—	—	—	—	—	—
18	AEROPLANE 'C'	FIGHTER	290·5	40·0	7·26	1/27	3·26	6 1/2	+0·63(6)	0·022	+0·65	−0·24	—	—	—	—	—	—	—	—
19	PROVOST	TRAINER	208	35·17	5·92	1/20	5·44	12 1/4	−0·72	0·107	−0·42	+0·08	—	—	—	—	—	—	—	—
									−1·13	0·125	−0·70	0·09	—	—	—	—	—	—	—	—
									−1·39	0·125	−0·91	0·13	—	—	—	—	—	—	—	—
(B) AIRCRAFT WITH SWEPTBACK WINGS, WITH TAIL UNITS																				
20	AEROPLANE 'D'	FIGHTER	273	31·7	8·61	1/30	1·18	2 3/4	—	—	—	—	−0·97	0·037	CENTRAL	PRO	+10 1/2	70·2	−0·90	0·150
									—	—	—	—	↓	↓	PRO	PRO	12 1/2	↓	↓	0·178
									—	—	—	—	↓	↓	CENTRAL	ANTI	−9 1/2	↓	↓	0·135
21	AEROPLANE 'E'	FIGHTER	344	33·5	10·25	1/30	1·39	3	−1·73	0·055	−1·46	~0·40	−1·21	0·051	CENTRAL	PRO	+9	33·7	−1·10	0·267
									—	—	—	—	↓	↓	PRO	PRO	9 1/2	↓	↓	0·282
(C) AIRCRAFT WITH DELTA WINGS, WITH TAIL UNITS																				
22	AEROPLANE 'F'	NIGHT-FIGHTER	900	52	17·30	1/40	2·20	4 3/4	−0·40	0·047	−0·28	0·70	−0·35	0·048	CENTRAL	PRO	3	36 1	−0·29	0·083
									—	—	—	—	↓	↓	PRO	PRO	5	↓	↓	0·138
(D) AIRCRAFT WITH SWEPTBACK WINGS, WITHOUT TAIL UNITS.																				
23	G.A. 01.	EXPERIMENTAL GLIDER	350	45·33	7·73	1/20	11·63	30	—	—	—	—	+0·56	0·088	CENTRAL	PRO(7)	1	74 0	0·60	0·014
									—	—	—	—	↓	↓	CENTRAL	ANTI	−5	↓	↓	0·041
									—	—	—	—	0·71	0·078	CENTRAL	PRO	+2 1/2	↓	0·73	0·034
									—	—	—	—	↓	↓	CENTRAL	ANTI	2	↓	↓	−0·027
24	G.A.L. 61	EXPERIMENTAL GLIDER	452	52·0	8·70	1/23	11·55	35	—	—	—	—	0·735	0·077	CENTRAL	ANTI(8)	~12	74 0	0·755	−0·162
25	AEROPLANE 'G'	EXPERIMENTAL	328	39·0	8·41	1/30	2·20	5 1/2	—	—	—	—	0·35	0·065	CENTRAL	PRO(9)	−3	29·5	0·39	−0·102
									—	—	—	—	↓	↓	CENTRAL	ANTI	+1 1/4	↓	↓	−0·042
									—	—	—	—	0·33	0·066	CENTRAL	PRO(10)	1 1/2	↓	0·37	+0·051
									—	—	—	—	↓	↓	CENTRAL	ANTI	−2	↓	↓	0·068
(E) AIRCRAFT WITH DELTA WINGS, WITHOUT TAIL UNITS.																				
26	AEROPLANE 'H'	EXPERIMENTAL	275	25·5	10·78	1/20	2·07(11)	5 1/4	−0·14	0·028	−0·08	0·23	0·13	0·042	CENTRAL	PRO(13)	+1	36·2	−0·08	0·028
			296	34·42	8·60	1/20	5·10(12)	9 1/4	—	—	—	—	↓	↓	CENTRAL	ANTI	−1/4	↓	↓	0·007

NOTES:-

(1) 'PRO' AND 'ANTI' INDICATE FULL PRO-SPIN OR ANTI-SPIN DEFLECTIONS.

(2) R IS ESTIMATED BY THE METHOD OF R. & M 2308 (REF. 5)

(3) AIRCRAFT DIMENSIONS FOR SPITFIRE WITH CLIPPED WINGS.

(4) THE RESULTS OF ROLLING-MOMENT TESTS ON THESE MODELS ARE GIVEN IN R.& M. 1967 (REF. 3)

(5) THE ROLLING AND YAWING VANES WERE MOUNTED ON THE SAME SPIKE. 13 1/2 IS ΔA FOR THE ROLLING VANE AND ΔA/A INCLUDES THIS.

(6) LOADING DISTRIBUTION WITH FULL WING-TIP FUEL TANKS

(7)&(10) LARGE DOWN ELEVON ANGLES IN THE 'ELEVATOR' SENSE, WITH THE 'AILERON' ANGLES SUPERIMPOSED.

(8),(9)&(13) DOWN ELEVON ANGLES IN THE 'ELEVATOR' SENSE LIMITED TO ≤5°. ANGLES IN THE 'AILERON' SENSE ARE SUPERIMPOSED ON THIS.

(11) DIMENSIONS FOR TESTS WITH APPLIED ROLLING MOMENTS

(12) DIMENSIONS FOR TESTS WITH 'AILERON' DEFLECTIONS

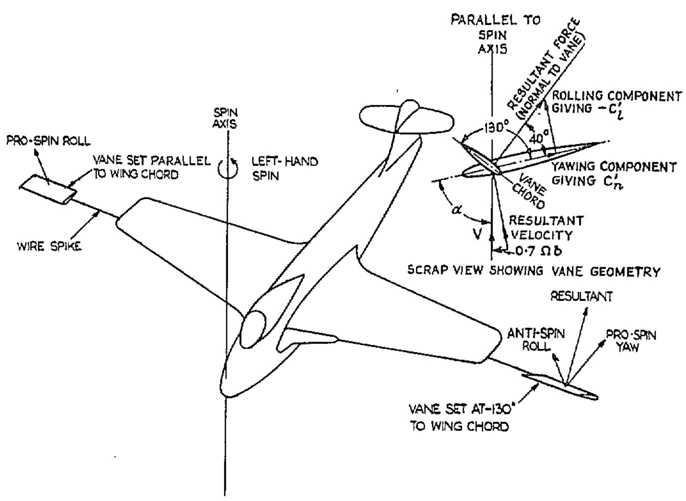


FIG. 1. Method of applying moments to spinning model.

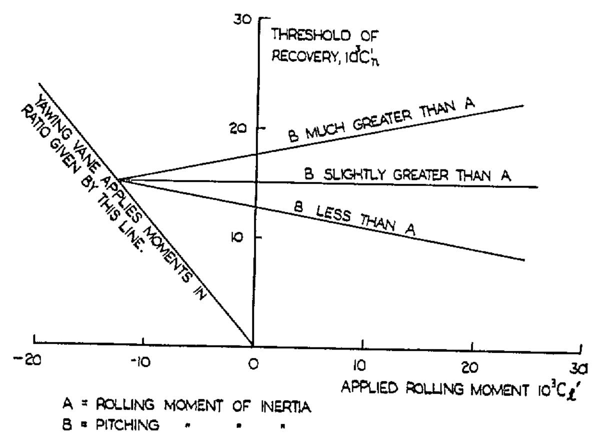
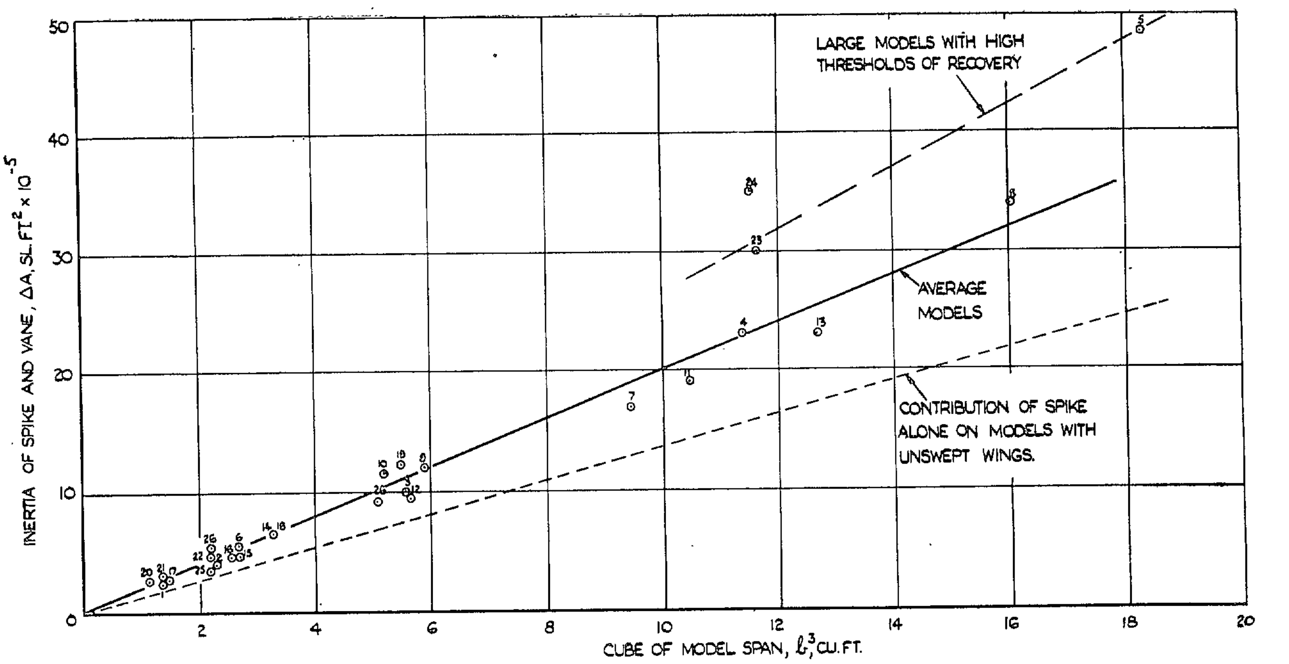
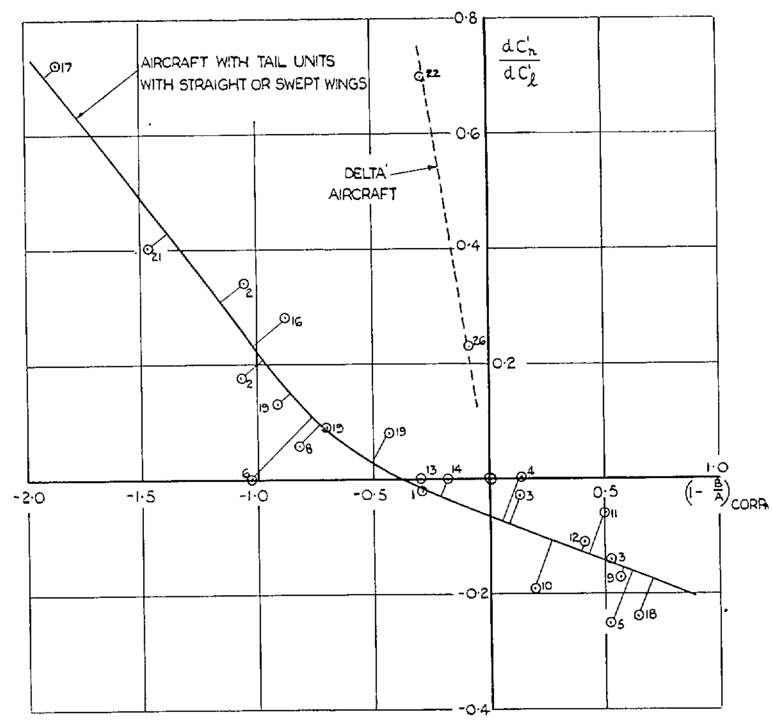


FIG. 2. Sketch showing effect of applied rolling moment on threshold of recovery.



NOTE:- THE NUMBERS REFER TO THE MODELS LISTED IN TABLE I

FIG. 3. Addition to rolling moment of inertia of spinning models due to a spike and vane mounted on one wing tip.



NOTES

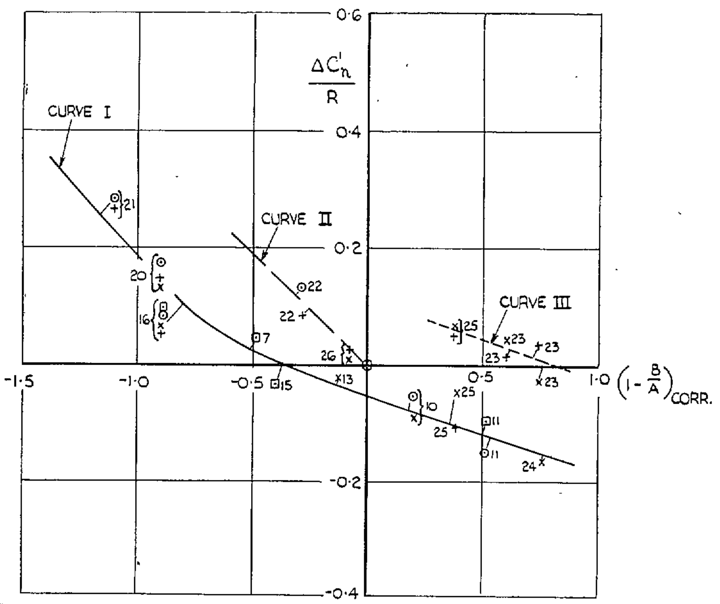
$\frac{dC'_n}{dC'_l}$ IS SLOPE OF CURVE OF THRESHOLD OF RECOVERY IN UNITS OF APPLIED YAWING MOMENT VS APPLIED ROLLING MOMENT FOR $-C'_n \tan 40° < C'_l < 20$.

$\left(1-\frac{B}{A}\right)_{CORR}$ IS CALCULATED FROM MODEL VALUES AT TIME OF TEST WITH A CORRECTION TO 'A' FOR THE INERTIA OF THE SPIKES AND VANES APPLYING THE MOMENTS TO THE MODEL.

THE NUMBERS REFER TO THE MODELS LISTED IN TABLE I.

FIG. 4. Relation between the effect of applied rolling moments on thresholds of recovery and the inertias A and B.

AILERONS DEFLECTED		SYMBOL
IN SPIN	IN RECOVERY	
CENTRAL	PRO-SPIN	+
PRO-SPIN	PRO-SPIN	⊙
CENTRAL	ANTI-SPIN	×
ANTI-SPIN	ANTI-SPIN	⊡



KEY:-

CURVE	AIRCRAFT TYPE
(I)	AIRCRAFT WITH TAIL UNITS WITH STRAIGHT OR SWEPT WINGS, AND TAILLESS AIRCRAFT ON WHICH THE DOWN ELEVON ANGLES IN THE ELEVATOR' SENSE ARE LIMITED TO < 5°
(II)	DELTA AIRCRAFT WITH THE SAME LIMITATION ON DOWN 'ELEVATOR' ANGLES
(III)	TAILLESS AIRCRAFT HAVING LARGE DOWN ELEVON ANGLES IN THE ELEVATOR' SENSE

NOTES :-

$\Delta C'_n$ IS CHANGE IN RECOVERY THRESHOLD DUE TO FULL DEFLECTION OF BOTH AILERONS.

R IS ROLLING MOMENT OF FULLY DEFLECTED AILERONS AS CALCULATED USING REPT. Nº AERO 2011; PRO-SPIN DEFLECTIONS ARE POSITIVE AND VICE VERSA

$\left(1-\frac{B}{A}\right)_{CORR}$ IS CALCULATED FROM MODEL VALUES AT TIME OF TEST, WITH A CORRECTION TO 'A FOR THE INERTIA OF THE SPIKES AND VANES APPLYING THE MOMENTS TO THE MODEL

THE NUMBERS REFER TO THE MODELS LISTED IN TABLE I.

FIG. 5. Effect of aileron deflections on thresholds of recovery of various models.
Note: Rept. No. Aero. 2011 has been published as R. & M. 2308.

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