ICAS-82-5.4.6

PREDICTION OF HIGH ALPHA FLIGHT CHARACTERISTICS UTILIZING ROTARY BALANCE DATA

William Bihrle, Jr.*
Bihrle Applied Research, Inc.
Jericho, New York

Abstract

Rotational flow aerodynamic data, as measured by a rotary balance at low Reynolds number, are used to analytically predict steady spin modes and post-stall motions. The excellent agreement obtained between predicted and full-scale flight results would indicate that use of low Reynolds number rotary balance data is sufficient for calculating steady-spin modes for military configurations and general aviation configurations not having large wing leading-edge radii. Considerations, however, in the application of these low Reynolds number data to steady-state spin analysis, as well as large angle, six degree-of-freedom high alpha studies, are discussed. Also, the procedure for developing a configuration highly resistant to spins is illustrated.

Nomenclature

C_m	pitching moment coefficient
C_n	yawing moment coefficient
$\Omega b/2V$	spin coefficient, positive for clockwise spin
δ_a	aileron deflection, deg
δ_d	differential tail deflection, deg
δ_e	elevator deflection, deg
δ_r	rudder deflection, deg
δ_{LEF}	leading-edge flap deflection, deg
L.E.	leading edge

I. Introduction

Since spins could not be predicted analytically in the past, spin tunnel and full-scale spin tests were employed to determine an airplane's spin characteristics. While these experimental techniques successfully identified the spin characteristics, they provided no insight into the factors responsible for the observed behavior and seldom influenced the aerodynamic configurations. Consequently, in recent years, full-scale military flight programs were reoriented towards documenting departure from controlled flight at high angles of attack and corresponding recovery techniques. NASA Langley Research Center continued traditional spin model testing and the development and validation of experimental and analytical techniques for the prediction of spin characteristics.

Rotational flow aerodynamics, as measured by a rotary balance, are a vital prerequisite for analytically predicting post-stall motions. Such a balance was developed, therefore, to measure the rotational flow aerodynamics(1) at various angles of attack, sideslip angles, spin radii, and control settings. Using these data, on-line steady spin modes may be analytically predicted(2) by solving the moment equations for steady equilibrium conditions. The rotary balance data may subsequently be used to compute post-stall motions such as the incipient, developed, and recovery phases of a spin by employing an appropriate, large angle, six degree-of-freedom computer program.

This paper presents the correlation obtained between predicted steady spins, using low Reynolds number rotary balance data, and spin model and full-scale flight results for several military and general aviation configurations. Considerations for the application of low Reynolds number data to steady-state spin analysis and to large angle, six degree-of-freedom high alpha studies are also discussed. Finally, the procedure for developing a configuration highly resistant to spins is illustrated.

II. Correlation Between Predicted and Experimentally Determined Spins

A computational method can be validated by demonstrating acceptable correlation between predicted and experimentally determined results. In this instance, however, both the method(2) for computing steady-state spin equilibrium conditions and the use of low Reynolds number rotary balance data must be justified. Consequently, low Reynolds number free-spinning dynamically ballasted model results obtained in the spin tunnel are compared with the predicted values to verify the computational method; whereas full-scale airplane results are reviewed to identify possible Reynolds number related difficulties. These data are presented in Table 1 for military and Tables 2 and 3 for general aviation configurations. It should be noted that the predicted steady spins presented in these tables were calculated using on-line rotary balance data, i.e., no smoothing, shifting, etc. of these data were performed.

The correlation obtained between predicted steady spins and spin model results is considered excellent and indicates the sufficiency of the computational method. As shown, no spins are obtained that had not been predicted and for each predicted spin mode, three possibilities exist in flight: the steady spin will be realized (models A,B,D,E,F,G,I), oscillatory about

*Associate Fellow AIAA

the steady spin values (models C,E), or non-existent (model C). The latter two conditions reflect the underlying spin mode's level of instability, which is illustrated by the model C results. For this model, two steady spin modes, moderately flat and flat, were predicted, but only a highly oscillatory spin about the predicted flat mode was encountered. These spin tunnel model results are attributed to the levels of instability existing at the predicted steady-state equilibrium conditions. To demonstrate this premise, the wing tips were modified to increase the stability of the spins. As shown, this modification affected the predicted steady spin modes only slightly, but caused the spin model to exhibit both of the predicted spin modes.

The correlation obtained between full-scale flight results and predicted steady spins is also considered excellent for the military configurations presented in Table 1. Unfortunately, not many documented spins are available since, as mentioned previously, full-scale spin demonstrations are no longer required. Fully developed spins are, therefore, seldom and only inadvertently encountered, e.g. airplane B, which encountered a spin while the controls were held in a spin recovery position.

As shown in Table 2, the level of agreement between predicted and full-scale flight results for general aviation configurations, while still considered excellent, can be somewhat less than that obtained for military configurations. Instances are also shown in which predicted spin modes are experienced by the spin model but not demonstrated by the full-scale airplane. This does not infer that these spin modes do not exist, only that the airplane was not able to generate the required equilibrium conditions. Since the wing characteristics are largely responsible for steep and moderately steep spins, the use of low Reynolds number data may adversely affect the accuracy of predicted spin modes. This is illustrated in Table 3, which presents the correlation obtained when the basic wings of models F and H were modified by incorporating large drooped leading-edges over part or all of the wing span. With these large leading-edge radii, the agreement between predicted and full-scale spins deteriorated appreciably.

The level of agreement between predicted and full-scale flight results would indicate that use of low Reynolds number rotary balance data is sufficient for calculating steady spin modes for military configurations and general aviation configurations not having large wing leading-edge radii. The use of low Reynolds number data in spin analysis is further discussed in the next section.

III. Reynolds Number Considerations

Since the rotary balance data are measured in the Langley Spin Tunnel at low Reynolds number, their validity is always of concern. Presently, there is no operational facility that can provide comparable data at Reynolds numbers approaching those of the full-scale airplanes. Recourse was taken, therefore, to compare rotary balance based spin predictions with full-scale results, as discussed above, and static rotary balance data (measured at $\Omega b/2V=0$) with equivalent data obtained at high Reynolds numbers.

A review of the static data has shown the stability and control characteristics to be reasonably well represented by low Reynolds number data except as noted herein. Military configurations have a more negative pitching moment at a given angle of attack than would be measured with the rotary balance model. This Reynolds number effect on pitching moment is not due to a difference in wing aerodynamics, but results from a larger cross-flow drag acting on the model forebody than on the airplane forebody. The magnitude of this discrepancy is a function of the forebody fineness ratio and shape, as well as its distance ahead of the center-of-gravity location. The greater the fineness ratio, moment arm, and distribution of the forebody volume in the horizontal plane, the greater the discrepancy. In general, the rotary balance models' pitching moment coefficients are up to .15 more positive than the airplanes' for alphas in the 45° to 90° range. An error of approximately .35 C_m was noted, however, for one configuration possessing all of the Reynolds number sensitive forebody characteristics.

Steady-State Spin Analysis

To ascertain the importance of these C_m errors, predicted steady-state spins were recalculated with the rotary balance data shifted so that the static ($\Omega b/2V=0$) values agreed with those obtained during high Reynolds number tests. For none of the longitudinally stable models tested to date did these pitching moment corrections significantly affect the predicted spin modes. This result was anticipated because of the excellent correlation obtained between predicted and full-scale flight determined spin modes and because of the ability of dynamically ballasted spin models to identify, fairly accurately, full-scale spin characteristics over the years. All the results to date indicate that steady spin modes can be predicted for military configurations using low Reynolds number rotary balance data. As a precautionary measure, however, when spins are predicted for a preliminary design, their sensitivity to larger negative pitching moments is also evaluated.

It should be noted that low Reynolds number testing can present a problem for a control-configured vehicle that is highly unstable longitudinally. If such a configuration had a Reynolds number sensitive forebody design, both the spin and rotary balance model could exhibit positive pitching moments over most of the 0-90° alpha range. Consequently, a nonspinning high alpha trimmed motion would be demonstrated and predicted by the spin model and rotary balance data, respectively. However, if, at high Reynolds number, a stable pitching moment curve having negative moments were shown to exist over some portion of the high alpha region, then a spin mode may be predicted using these data instead of a high alpha trim condition.

As shown in the previous section, the ability to predict spin modes is appreciably degraded for a general aviation configuration having a large wing leading-edge radius. Obviously, this situation can be anticipated if the measured static and/or rotational flow pitching and rolling moment characteristics are shown to vary with Reynolds number. A technique for overcoming this problem remains to be developed. One of several possibilities is the selection of an equivalent model airfoil section that duplicates, at low Reynolds number, the full-scale wing stall aerodynamic characteristics. Use of an equivalent airfoil section at high alphas (above 35°), however, would probably result in higher autorotative moments than would be obtained on the airplane; thereby requiring some changes in the present test procedure.

Large Angle, Six Degree-of-Freedom Computations

If the stability of a predicted spin is to be determined using a large angle, six degree-of-freedom computer program, the direct application of rotary balance data would suffice, as was the case in predicting steady-state spin modes. In this instance, dynamic derivatives must be included in the aerodynamic model and the computations would be initiated for conditions near the predicted spin equilibrium values. The ensuing motion would be indicative of the spin's stability. If, however, time histories were to be computed for a maneuver beginning in the unstalled flight regime and proceeding into the post-stall region, as would be the case for a departure or spin susceptibility investigation, the direct use of low Reynolds number rotary balance data would be improper for some configurations, as discussed below.

Static force tests show a yawing moment at zero sideslip in the 40° to 70° angle-of-attack range for most fighter configurations due to asymmetrical vortex shedding at the nose. The magnitude of this moment is greater for the rotary balance model than the airplane because of the correspondingly greater cross-flow drag experienced at low Reynolds number, as mentioned previously in regard to static pitching moments. Therefore, for a proper representation, the rotary balance determined C_n and C_m value at $\Omega b/2V=0$ should be shifted to the lower value obtained at high Reynolds number.

Although the magnitude of the yawing moment offset at full-scale Reynolds number may be less than that measured at low Reynolds number, the influence of rotation on yawing moment is assumed not to be significantly affected by Reynolds number. That is, a damped or propelling characteristic demonstrated at low Reynolds number should reflect the full-scale airplane characteristics. This belief is based on the following observations: Flat and moderately flat spin rates are uniquely dependent on the C_n vs $\Omega b/2V$* relationship existing at the spin angle of attack; i.e., propelling moments exist up to approximately the spin equilibrium rotation rate and then are damped for higher rotation rates. Since the spin rates and angle of attack identified by spin model and rotary balance data agree well with full-scale values, it would appear that the C_n vs $\Omega b/2V$ relationships determined at low Reynolds number are proper. The relationships also appear valid at lower alphas since the effect of off-set yawing moments on airplane behavior seems to correlate with rotary balance determined C_n vs $\Omega b/2V$ characteristics. That is, directional "nose slice" departures are experienced during a longitudinal maneuver for configurations shown to have propelling rotational yawing moments; whereas this is not the case when damped yawing moments are indicated.

IV. Configuration Definition Procedures

The variation of the three aerodynamic moments with rotation determines the existence and nature of an airplane's spin modes. The source of these moments can be determined by examining the contribution of each airplane component. Consequently, component build-up tests are conducted first to determine the contribution of the body, wing, horizontal tail, etc. to the moment characteristics. Then the rotational flow aerodynamics are obtained for the complete configuration with various control settings. As mentioned previously, steady developed spins can be predicted concurrently with wind tunnel tests. Consequently, if steady spins are predicted, sufficient insight into the causes will have been established to permit the selection of judicious configuration or control modifications. The effectiveness of these

*Rates of rotation have been traditionally expressed nondimensionally in terms of the linear and angular velocities V and Ω, respectively, and half the wing span. Thus the expression $\Omega b/2V$ is the ratio of the wing tip speed to the forward velocity speed.

modifications in meeting the desired design objectives are then verified with additional rotary balance tests. Some of these procedures are illustrated below for a general aviation and a military configuration.

General Aviation Configuration

Fig. 1 presents the rotational yawing moment characteristics obtained at 60° angle of attack for a general aviation configuration. Autorotative* yawing moments occur over a significant $\Omega b/2V$ range for this configuration with undeflected controls. Also presented in Fig. 1 are the yawing moment characteristics attributed to the wing, body, and tails. It can be seen that the airplane's autorotative moments are caused by the body and the interference of the horizontal tail on the vertical tail. In this instance, the interference is such that the large damping contribution of the vertical tail becomes propelling in the presence of the horizontal tail. The body and/or the tail design would be candidates for further investigation if an undesirable steady spin mode were predicted for this configuration.

Military Configuration

The rotational rolling, pitching, and yawing moment characteristics obtained for neutral controls at 40° angle of attack are presented in Fig. 2 for a military configuration. Autorotative rolling and yawing moments exist over a significant $\Omega b/2V$ range. In addition, the configuration exhibits increasing nose-up pitching moments with increasing rotation rate and an off-set yawing moment at $\Omega b/2V=0$. Such characteristics are highly indicative of a susceptibility to depart from controlled flight in the alpha range where they occur.

Fig. 2 also presents the contribution of the body, wing, and tails to these characteristics. It can be seen that the autorotative rolling moment is mainly due to the wing; whereas the pitching and yawing moment characteristics are dictated by the body. The influence of the body is further illustrated in Fig. 3, which presents the component yawing moment characteristics obtained for the same configuration at an angle of attack of 50°, where the body cross-flow drag effect is close to maximum. It is shown that the body alone is completely responsible for both the off-set moment and autorotative characteristics. Fig. 3 further illustrates that, in this case, these yawing moment characteristics are attributable to the forebody, since the large propelling moments become highly damped when very small nose strakes are mounted on the forebody.

The influence of the forebody strakes at 40° angle of attack on the yawing as well as the rolling and pitching moment characteristics is also shown in Fig. 2. The nose-up pitching moment characteristic is eliminated and the propelling yawing moment becomes highly damped. Also, a favorable forebody influence on the wing is indicated when the strakes are present, since the configuration becomes damped in roll.

A flat spin mode was predicted for this configuration. Consequently, the ability of the strakes to minimize departure susceptibility was examined using a large angle, six degree-of-freedom computer program. The effect of the strakes is depicted in Fig. 4, which presents the resulting motions obtained with and without the strakes for the identified control inputs. Without strakes, a departure culminating in a flat spin was calculated; whereas the airplane with strakes did not depart.

*In a right spin (positive $\Omega b/2V$), positive yawing and rolling moments are autorotative, i.e., propelling rather than damping.

References

1. Bihrle, W., Jr., and Bowman, J.S., Jr.: Influence of Wing, Fuselage, and Tail Design on Rotational Flow Aerodynamics Beyond Maximum Lift. Journal of Aircraft, Vol. 18, Nov. 1981, pp. 920-925.

2. Bihrle, W., Jr., and Barnhart, B.: Spin Prediction Techniques. AIAA Paper 80-1564-CP, Aug. 1980.

Table 1 Experimental and predicted spin[a] modes for military configurations

Model		Controls					Spin mode	
		δ_e	δ_a	δ_r		α	sec/turn	$\Omega b/2V$
A		0	0	0	Spin tunnel	66	8.0	.05
					Predicted	66	8.5	.05
		-30	30	-30	Spin tunnel	83	2.7	.14
					Predicted	81	1.9	.23
B		0	0	0	Spin tunnel	83	2.3	.14
					Predicted	81	2.5	.14
		+5	-30	+30	Flight test	78	3.8	.08
					Predicted	78	3.7	.09
C		-20	30	-30	Spin tunnel	85[b]	1.5	.32
					Predicted[c]	58	4.0	.09
						81	1.5	.32
+Wing tip					Spin tunnel[c]	64[b]	3.7	.12
						87[b]	1.5	.34
					Predicted[c]	63	3.7	.12
						81	1.6	.32
+Wing tip & body strake					Spin tunnel[c]	70[b]	5.2	.08
						87[b]	1.7	.28
					Predicted[c]	66	5.5	.08
						81	1.8	.25
	δ_{LEF}		δ_d/δ_a					
D	0	0	6/20	-15	Flight test	75	3.0	.18
					Spin tunnel	81	2.4	.24
					Predicted	80	2.7	.21
+Body tanks					Spin tunnel	84	2.1	.28
					Predicted	81	2.3	.24
E	34	0	20/25	0	Flight test	85	2.7	.14
	35				Spin tunnel	83	2.5	.18
	30				Predicted	83	2.5	.16
	34	0	0	0	Flight test	70[b]	5.1	.08
	35				Spin tunnel	70[b]	5.3	.07
	30				Predicted	69	5.2	.07

[a]Spins shown are to the right. [b]Oscillatory spin. [c]Multiple spin modes.

Table 2 Experimental and predicted spin[a] modes for general aviation configurations

Model	δ_e	δ_a	δ_r		α	Spin Mode sec/turn	$\Omega b/2V$
F	-25	0	-25	Flight test	39	2.3	.27
				Spin tunnel[c]	38	2.5	.22
					77	1.1	.83
				Predicted[c]	38	2.2	.23
					77	1.2	.81
	0	0	0	Flight test[b]	54	1.7	.46
				Predicted	36	1.7	.32
					55	1.7	.39
					79	1.0	1.0
				Spin tunnel[b]	42	1.5	.38
					78	1.0	1.0
				Predicted[c]	35	1.5	.38
					77	1.0	1.0
G	-20	12.5	2.0	Flight test	20	1.8	.34
				Spin tunnel	22	2.0	.31
				Predicted	18	1.3	.40
H	-15	15	-25	Flight test	29	2.2	.29
				Predicted	23	1.7	.29
I	-10	0	-26	Flight test	44	2.8	.23
				Spin tunnel	30	2.3	.30
				Predicted	33	2.6	.27

[a]Spins shown are to the right. [b]Different inertia distribution for flight and spin model. [c]Multiple spin modes.

Table 3 Experimental and predicted spin[a] modes for general aviation configurations having drooped wing leading edges

Model	δ_e	δ_a	δ_r		α	Spin mode sec/turn	$\Omega b/2V$
F (full span L.E.droop)	-25	+22.5	-25	Flight test	63	1.7	.45
				Predicted[b]	47	2.5	.25
					82	1.0	1.00
(outboard L.E. droop)				Flight test	25	3.5	.13
				Predicted[b]	38	2.5	.20
					81	1.0	.98
H (full span L.E.droop)	-15	-25	-15	Flight test	56	2.5	.36
				Predicted	36	1.8	.38

[a]Spins shown are to the right. [b]Multiple spin modes.

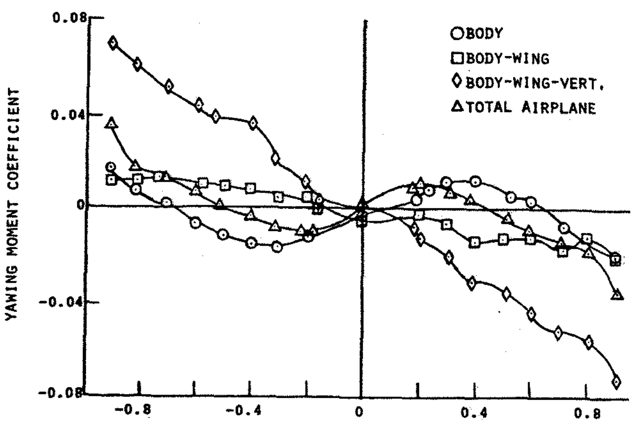

Fig. 1 Influence of airplane components on yawing moment characteristics obtained at alpha 60° for a general aviation configuration.

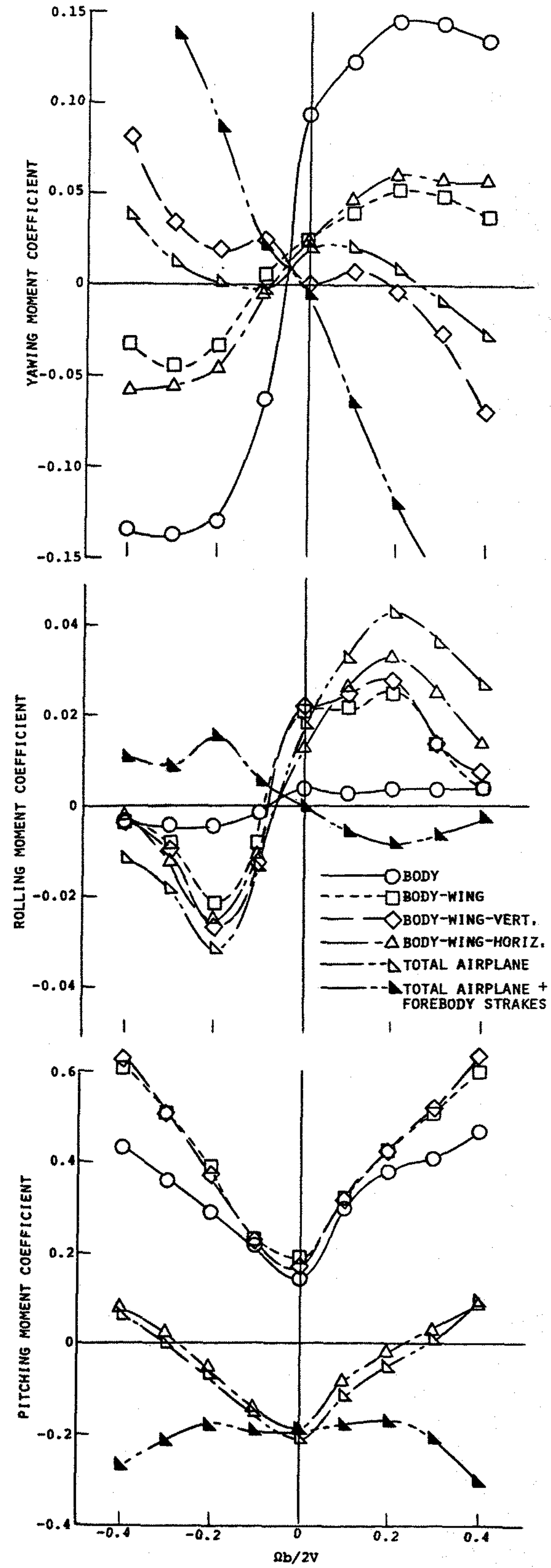

Fig. 2 Influence of airplane components and nose strakes mounted on the forebody on moment characteristics obtained at alpha 40° for a military configuration.

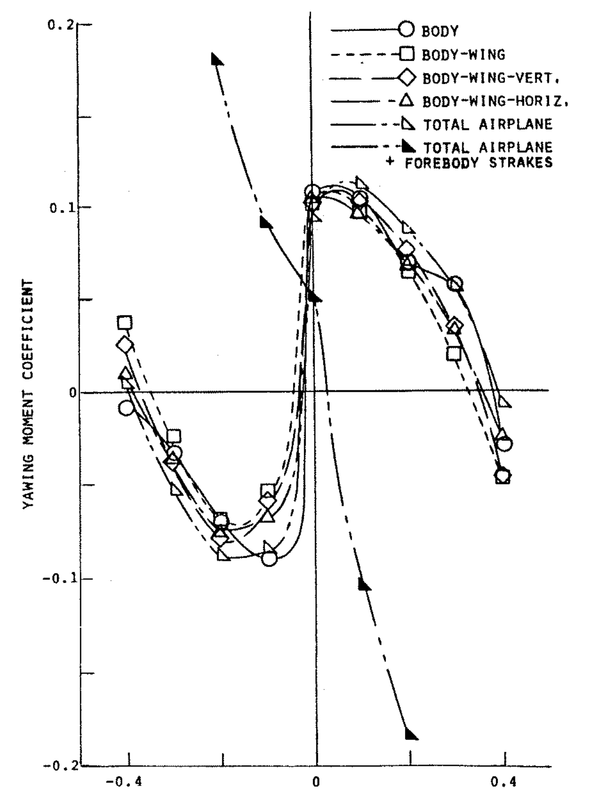

Fig. 3 Influence of airplane components and nose strakes mounted on the forebody on yawing moment characteristics obtained at alpha 50° for a military configuration.

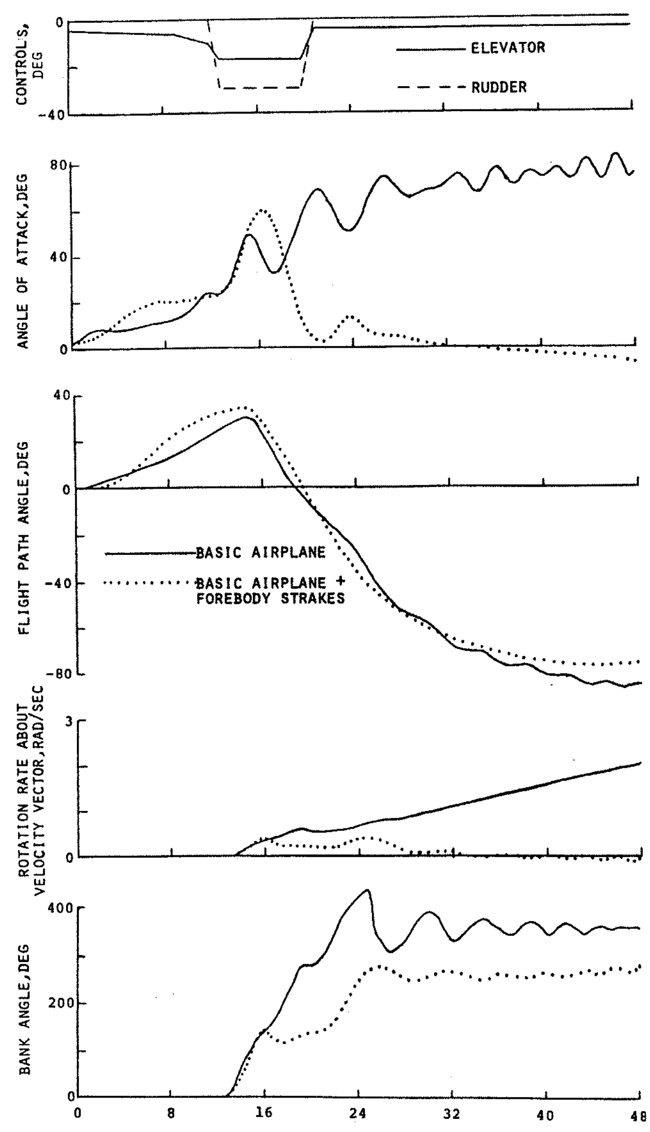

Fig. 4 Influence of nose strakes mounted on the forebody on computed airplane motions.