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DEVELOPMENT OF A ROLLING MANEUVER SPECTRUM FROM STATISTICAL FLIGHT LOADS DATA

John W. Rustenburg

Aeronautical Systems Division
Wright-Patterson Air Force Base, Ohio

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13. ABSTRACT

Absence of clearly defined antisymmetrical fatigue load spectra in military specifications has resulted in questions regarding the validity of rolling maneuver spectra applied to the B-1 design. In response, multiparameter flight loads data measured on the F-5A and F/105D aircraft was evaluated and used in the development of a probability of exceedance curve for the normalized wing tip helix angle. The normalized probability curve can be used in conjunction with any specified normal load factor spectrum and the airplane's maximum pb/2V capabilities to determine the occurrence rate of rolling velocity peaks. The approach should provide at least a first order estimate of possible rolling velocity spectra which can be applied in aircraft fatigue design for antisymmetrical maneuver conditions.

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DEVELOPMENT OF A ROLLING MANEUVER SPECTRUM FROM STATISTICAL FLIGHT LOADS DATA

JOHN W. RUSTENBURG

FOREWORD

This report was prepared by John W. Rustenburg, Airframe Division, Deputy for B-1, under System 139A, B-1.

The report results from a study to determine rolling velocity occurrence spectra for possible application in the B-1 fatigue design. The manuscript was released by the author in December 1972 for publication as a technical report.

The technical report has been reviewed and is approved.

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SYMBOLS

b	wing span, feet
h	altitude, feet
M	mach number
N_z	normal load factor, g
p	rolling velocity, degrees/second
V	true airspeed, feet/second
V_e	equivalent airspeed, knots
δ_a	aileron deflection
Φ	bank angle

SECTION I

INTRODUCTION

In recent years increasing concern has been expressed about the application of antisymmetrical maneuver spectra to airplane fatigue design. This concern has been formalized in a MIL-A-8866A (USAF) requirement "to proportion fatigue spectra between symmetrical and unsymmetrical maneuvers." Unfortunately the specification does not define actual antisymmetrical maneuver spectra to be used. This omission has necessitated the application in fatigue design of rather arbitrarily determined antisymmetric maneuver spectra. These antisymmetric spectra have usually taken the form of rolling maneuver spectra; these being considered to be the most critical antisymmetric maneuvers in affecting structural loads.

It was decided to study available F-5A and F-105D measured multiparameter flight loads data to attempt derivation of a more realistic rolling maneuver spectrum than would result from purely arbitrary approaches.

Rolling tail loads and those items stressed by the redistribution of loads due to roll control displacement are usually most sensitive to roll rate. Rolling maneuver loads calculations for the B-1 have confirmed that maximum loads occur at the time of maximum rolling velocity with insignificant contributions due to rolling acceleration. For this reason the development of a rolling maneuver spectrum was oriented towards deriving a rolling velocity or roll rate spectrum.

SECTION II

ANALYSIS OF DATA

The most common technique to evaluate the distribution and influence of a parameter is to determine the probability distribution or relative frequency of the parameter peak values. Of additional value is the evaluation of such parameter distributions correlated with simultaneous values of other variables.

Bivariate tables from References 1 and 2 which summarize the parameters of load factor, rolling velocity, altitude and speed are presented in Tables I through VIII. The Tables present the number of parameter peaks accumulated within prescribed ranges and listed at the lower limit of each parameter range. This data was transformed into probability or relative frequency distributions of parameter peak values. Figures 1 and 2 present the roll rate peaks as a function of normal load factor. It can be seen that the relative frequency of roll rate peaks is fairly consistent over the load factor range. Larger data scatter is mostly the result of a few or a single occurrence in some of the parameter ranges. A major conclusion to be drawn is that the probability of encounter of a given rolling velocity is not significantly affected by the normal load factor magnitude existing at the time. For practical purposes this means that a single roll maneuver probability curve could be considered applicable to all normal load factor levels.

References 1 and 2 considered load factor peaks and roll rate peaks to be "active" when they occurred outside the thresholds $0 < N_z < 2.0$, and -30 degr./sec. $< p <$ 30 degr./sec. It was the interpretation of Reference 1 that a flight maneuver is truly antisymmetric only when both the rolling velocity and load factor are outside their respective thresholds. Based on this interpretation and the assumption that the probability of a rolling velocity and a normal load factor occurrence are dependent functions, the percentage of true rolling maneuvers can be determined as a function of the number of positive normal load factor peaks.

An additional refinement would be to include only load factor peaks which occurred up to the maximum load factor level at which roll velocity peaks were measured. The inherent assumption is that this accounts for the occurrences up to the airplane's unsymmetrical maneuver load factor limit. From Tables I, II, V and VI this results in a percentage of roll peak occurrences in terms of the positive normal maneuver peak occurrences of (1137/9350) x 100 = 12.2% for the F-5A and (278/1956) x 100 = 14.2% for the F-105D aircraft. For future applications the use of an average value of 13% is suggested.

Examination of Tables II and VI shows that the number of positive and negative p values are almost symmetric about the roll rate thresholds. This suggests that on the average an equal number of rolls are performed in either direction. Figure 3 presents a description of a simplified rolling (turning) maneuver as obtained from Reference 7. The roll control is displaced, held and returned to neutral with proper timing and displacement to bank the airplane up to an angle necessary to match the load factor. This bank angle and load factor are held steady until the desired change in heading has been accomplished. Then the roll control is displaced, held and returned to neutral in order to return the aircraft to straight and level flight. Review of References 4 and 8 indicates this maneuver to be typical of service operations as well. Based on the above, the rolling maneuver occurrences equal to 13% of the normal load factor occurrences existing below the unsymmetrical maneuver load factor limit should consist of an equal number of left and right rolls.

The data from Tables III, IV, VII and VIII was used to obtain relative frequency curves of roll peaks as a function of altitude and speed. The results are shown plotted in Figures 4, 5, 6 and 7. As can be seen, the majority of roll peaks occurred within certain speed and altitude bands as exhibited by the curve peaks. As will be evident later, this fact is of some value in the normalization of the basic data.

SECTION III

NORMALIZATION OF DATA

A criterion in common use for the evaluation of lateral control effectiveness is the non-dimensional parameter $\frac{pb}{2V}$ or the wing tip helix angle. Flight research has indicated that a pilot's concept of adequate control power is also tied closer to this parameter than the actual rolling velocity. Unfortunately, the data presented in Tables I through VIII is not in a form which allows a direct determination of the $\frac{pb}{2V}$ parameter.

Determination of the helix angle parameter requires knowledge of the true velocity. For the data available in Tables I through VIII the calculation of true velocity is less affected by the variation in measured altitude than by the variation in measured V_e or Mach number. Figures 4 through 7 provide graphical support that the use of a constant altitude representative of the majority of roll peak occurrences is justified and will have much less effect on the final $\frac{pb}{2V}$ values than the assumption of constant V_e or Mach number. Therefore, using a constant altitude as determined by the curve peaks of Figures 4 and 7, values of $\frac{pb}{2V}$ were calculated for all roll peak velocity increments available in Tables IV and VIII. The number of occurrences of $\frac{pb}{2V}$ values within intervals of incremental $\Delta\frac{pb}{2V} = 0.005$ radians/second were then tabulated to obtain a frequency distribution for $\frac{pb}{2V}$. The probability of exceedance distribution was then obtained by progressively summing (starting with the frequency of the largest value of $\frac{pb}{2V}$) the frequency distribution and then by dividing each sum by the total number of occurrences. The resulting distributions are plotted in Figure 8.

The magnitude of measured rolling velocity peaks is obviously dependent on the airplane's capability and some form of normalization of the data is necessary before it can be applied to other aircraft.

It has been assumed that a pilot utilizes an aircraft in direct proportion to its capability. Comparisons of maximum parameter peak values measured during combat or training missions with those determined during the aircraft CAT II flight tests support the validity of the assumption. A proportionality constant can then be determined by dividing the recorded value of any parameter peak by the maximum recorded or analytical value of that parameter. For example:

$$R_p = \frac{\left(\frac{pb}{2V}\right)_{\text{actual recorded}}}{\left(\frac{pb}{2V}\right)_{\text{maximum recorded}}}$$

In this manner the data presented in Figure 8 was normalized by dividing all measured wing tip helix angle values by the maximum measured value. The resulting normalized rolling maneuver probability distributions are presented in Figure 9.

SECTION IV

COMPARISONS WITH OTHER AIRCRAFT

The wing tip helix angle data points of Figure 8 were normalized to eliminate the effects of aircraft capability or type. The effectiveness of this procedure may be further checked by comparisons with the normalized data of other aircraft.

Figure 10 presents the probability of exceeding the parameter $\frac{pb}{2V}$ for the F-84F airplane as obtained from Reference 6. The curve is based on data measured during operational training missions, and can be normalized in the same manner as used for the data of References 1 and 2. Figure 11 shows the comparison of the F-84F with the F-5A, and F-105D aircraft. It can be seen that the R_p distribution based on the F-84F data is very close to that calculated for the F-105D and in general agreement with the F-5A.

Tables IX through XIII present flight loads data measured on an F-102A airplane as obtained from Reference 9. The data resulted from an effort to re-evaluate the F-102A useful operational life based on actual in-flight loads and stresses. Coincident with this effort eight-channel data (airspeed, altitude, three-axes linear accelerations and rotational velocities) were measured for application to structural design criteria.

In order to make meaningful comparisons, identical threshold values must be used. Since the F-5A and F-105D data was based on a roll rate threshold of 30 degr./sec., the F-102A roll rate occurrences below 0.52 radians/sec. were deleted from further consideration.

The large velocity increment from 0 to 250 knots does not allow a high level of confidence in the calculated $\frac{pb}{2V}$ values for this increment.

The magnitude of the low speeds below 250 knots must thus be defined more accurately. Consideration of the F-102A take-off, landing and approach speeds, as well as review of the processed data suggests an approximate value of 200 knots. The roll rate occurrences in the increment from 0 to 250 knots were thus assumed to occur at a velocity of 200 knots.

Determination of the final R_p frequency distribution was accomplished in the same manner as used for the F-105D and F-5A data except for the fact that the actual altitudes and speeds could be correlated as seen in Tables IX through XIII. Figure 11 shows the comparison of the F-102A with the F-5A, F-105D and F-84F aircraft.

Quite good agreement is shown for all aircraft even though the mission usage was considerably different. Based on this agreement it is postulated that the variation in probability of exceedance in the ratio R_p is little affected by mission differences. A probability curve based on the data points for all four aircraft and presented in Figure 12 is proposed as the statistical model for the rolling maneuvers of any aircraft. For future designs the effect of airplane type can be accounted for through denormalization of the curve using the airplane's maximum determined $\frac{pb}{2V}$ capability.

Figures 13 and 14 present the probability distributions for the normal load factor and roll rate for the F-84F. These curves are based on threshold values of 1.0 "g" for load factor and 0.4 rad./sec. for roll rate. The data in References 1 and 2 is based on threshold values of 2.0 "g" and 3^ degr./sec. for the normal load factor and rolling velocity respectively.

From Figure 13 it is seen that the probability of exceedance of 2.0 "g" equals 0.27 for the F-84F. From Figure 14 the probability of exceedance of a roll rate of 30 degr./sec. equals 0.68 for this aircraft. The number of exceedances above the new thresholds is then 0.27 x 7024 = 1896 for the normal load factor and 0.68 x 2256 = 1534 for the roll rate. An unsymmetrical maneuver load factor limit is not specified for the F-84F. All 1896 load factor occurrences are therefore applicable. The 1534 roll rate occurrences are distributed over the entire airplane normal load factor range and include a significant number while the load factor was below the 2.0 "g" threshold. How large this number is cannot be determined from the data in Reference 6. However, the data in Reference 1 and 2 suggest this to be on the average about 85% of the total. The number of roll rate peaks which occurred while the load factor was outside its threshold would then be (1.0 - .85) x 1534 = 230. This results in a percentage of roll peak occurrences as a function of normal maneuver occurrences of (230/1896) x 100 = 12.1%. This value is amazingly close to the average value of 13% suggested previously in the study.

SECTION V

APPLICATION OF RESULTS

Even though the effects of aircraft type have been accounted for in the development of the statistical rolling maneuver model, the actual number of occurrences of roll peak values will still be dependent on aircraft mission.

Review of the mission phase data in References 1 and 2 shows that the maximum number of rolling maneuvers, in terms of occurrences per hour, were measured during low angle bombing and ground gunnery runs. The remaining rolling maneuvers are distributed mainly in the descent, loiter and cruise phases. The rolling maneuver occurrences appear therefore to be quite dependent on mission segment. The MIL-A-8866A (USAF) specification makes allowance for variation in mission segments in its definition of the maneuver load factor spectra requirements. The relative severity of these spectra across the different mission segments is reasonably consistent with the relative measured load factor occurrences within comparable mission segments of References 1 and 2. Figure 15 presents a comparison of the specified and measured load factor occurrences for the data from Reference 1. Based on this comparison it would appear that when using the MIL-A-8866A specified maneuver spectra in a design, that the rolling maneuver spectra based on 13% of the number of normal load factor up to and including the unsymmetrical maneuver load factor would be distributed in a reasonable manner across all mission segments. It is assumed that this will hold for all classes of airplanes.

To determine the abruptness of a roll maneuver, statistical information on the time to reach the rolling velocity would be required. This information is not available but could be obtained from special studies utilizing the original time histories. Any specified maneuver abruptness would at present have to be based on rather arbitrary assumptions.

For many years the symmetrical loads to be used for fatigue purposes have been based on balanced conditions. There is no reason why this approach cannot also be used in the determination of loads for antisymmetrical maneuvers. Application of control deflections necessary to overcome the airplane damping in roll and provide the desired roll rate at a given load factor level would then provide an acceptable alternative to the specification of maneuver abruptness.

In certain cases an airplane's maximum rolling velocity or $\frac{pb}{2V}$ is reached only after the airplane has rolled through excessively large angles which exceed any design requirements. It is then more realistic to consider maximum rolling velocities attainable within a bank to bank roll, where the bank angles are as determined by the design maneuver load factors.

In summary, all previously discussed considerations may be combined to form the following general procedure for determining the rolling maneuver spectra for any aircraft.

1. Divide the airplane's mission profiles into the necessary number of flight segments or usage blocks.

2. Determine the maximum available value of the helix angle $\frac{pb}{2V}$ for each flight segment.

3. From Figure 12 calculate the probability of exceeding $\frac{pb}{2V}$.

4. Using the speed V and the dimension b/2 for each segment, calculate the probability of exceeding rolling velocities.

5. For each segment determine the load factor occurrences which include rolling maneuvers by taking 13% of the specified load factor spectrum up to and including the unsymmetric maneuver load factor.

6. Distribute the rolling velocities at each load factor level according to the probability curves derived in 3 above.

SECTION VI

CONCLUSIONS

The multiparameter flight loads data measured on the F-5A and F-105D aircraft has been used in the development of a generalized wing tip helix angle probability of exceedance curve. This curve may be used with the analytical maximum value of the parameter $\frac{pb}{2V}$ to estimate the probability of exceedance of rolling velocity magnitudes for any aircraft.

It has also been determined that the number of occurrences of a rolling condition may be considered equal to 13% of the number of positive normal load factor occurrences when specified for an aircraft type according to the MIL-A-8866A specification. Since all aircraft generally perform the same types of maneuvers, the parameter time histories will be identical, and the number of rolling occurrences will be equally divided between left and right rolling conditions for all aircraft.

Comparisons with available F-84F and F-102A data have provided increased confidence in the approach of this study. Although the results are encouraging, data comparison with other types of aircraft is desirable and necessary. Nevertheless, the present approach does provide a more realistic description of antisymmetrical maneuver spectra than was available previously. At the same time it is realized that the number of load peaks on some aircraft component is not necessarily directly related to the number of peaks of a single parameter. However, for purposes of component loading spectra for rolling conditions the rolling velocity parameter is definitely the most significant and should provide adequate results.

Those rolling velocities which occur below the threshold may be considered to represent symmetrical load conditions.

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TABLE I

F-5A LOAD FACTOR PEAKS vs ROLL RATE

p (roll rate)

N_z	-150	-120	-90	-60	-30	0	30	60	90	120	150	180	210	TOTAL
7					3									3
6.5					6	4								10
6.0					28	22								50
5.5			1	2	78	67	1							149
5.0			1	2	200	182	2							387
4.5				5	283	291	4	1	1					585
4.0			1	5	281	336	5							628
3.5				5	313	400	7	1					1	727
3.0			1	10	456	708	6	6	1	1				1189
2.5	1	2		7	882	1352	17	7	2		2			2272
2.0	1		3	13	1364	2021	8	1	1			1		
0.0														
-0.5			1		12	16	3							32
-1.0			1	1	6	3								11
-1.5					2	5								7
-2.0					2									2
TOTAL	2	2	9	50	3916	5407	53	16	5	1	2	1	1	9465

TABLE II

F-5A ROLL RATE PEAKS vs NORMAL LOAD FACTOR

p	N_z (normal load factor)											TOTAL
	-0.5	0.0	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.5	
210			1									1
180		1	1	1		1						4
150		9	1	2	1							13
120		26	8	6	1	1						42
90		74	11	3	1	1	1					91
60	1	368	26	13	5	2						415
30		2308	161	105	52	32	19	9	2	1		2689
0												
-30												
-60		1964	241	124	85	51	27	18	6	4	1	2531
-90	1	333	36	24	10	5	7	2	2			419
-120		93	9	10	2	1						115
-150		26	3	1								30
-180		3	1									4
TOTAL	2	5215	449	289	157	94	53	29	10	5	1	6354

TABLE III

F-5A ROLL RATE PEAKS vs ALTITUDE

p	h (altitude)							TOTAL
	<2000	2000	5000	10,000	15,000	20,000	25,000	
210			1					1
180	2	2						4
150	5	3	4			1		13
120	13	13	10	3		2	1	42
90	27	34	17	9	1	3		91
60	137	160	94	20	2	2		415
30	581	1162	806	112	14	8	6	2689
0								
-30								
-60	621	1109	683	95	15	3	5	2531
-90	165	159	73	13	5	4		419
-120	51	36	15	2	7	4		115
-150	4	13	5	5	2	1		30
-180		2	1			1		4
TOTAL	1606	2693	1709	259	46	29	12	6354

TABLE IV

F-5A ROLL RATE PEAKS vs EQUIVALENT AIRSPEED

p	V_e (equivalent airspeed)								TOTAL
	150	200	250	300	350	400	450	500	
210					1				1
180						4			4
150				2	6	3	2		13
120			3	11	10	14	4		42
90			6	35	29	19	2		91
60		2	36	164	117	80	16		415
30	2	53	289	890	797	480	169	9	2689
0									
-30									
-60	1	33	240	784	686	569	198	20	2531
-90	1		44	145	120	73	35	1	419
-120			7	60	27	15	6		115
-150			2	14	10	3	1		30
-180				1	3				4
TOTAL	4	88	627	2106	1806	1260	433	30	6354

TABLE V

F-105D LOAD FACTOR PEAKS vs ROLL RATE

N_z	p (roll ra)						TOTAL
	-90	-60	-30	0	30	60	
7.5			1				1
7.0			1	2			3
6.5			3	1			4
6.0			4	5			9
5.5			18	13			31
5.0		1	18	15			34
4.5		1	21	19			41
4.0			23	33	1		57
3.5		1	47	60			108
3.0		2	127	106	1		236
2.5		7	265	242	1		515
2.0	1	8	445	475	4	1	934
0.0							
-0.5		2	20	12	1	1	36
-1.0				1			1
TOTAL	1	22	993	984	8	2	2010

TABLE VI

F-105D ROLL RATE PEAKS vs NORMAL LOAD FACTOR

p	N_z (normal load factor)											TOTAL
	0.0	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	
120		1										1
90	5											5
60	25	6	5	2	1	1		1				41
30	264	61	25	8	11	4	4	1	1	1		380
0												
-30												
-60	218	61	30	10	10	7	2	1	1	1	1	342
-90	17	11	2	4	3							37
-120	2					1						3
TOTAL	531	140	62	24	25	13	6	3	2	2	1	809

TABLE VII

F-105D ROLL RATE PEAKS vs ALTITUDE

p	h (altitude) <2000	2000	5000	10,000	15,000	20,000	25,000	30,000	TOTAL
120					1		1		2
90			4	3	3	6	4		20
60	1	20	49	35	11	6	8	1	131
30	12	109	372	303	140	52	20	1	1009
0									
-30									
-60	9	103	403	271	170	56	27	1	1040
-90	1	27	46	21	8	9	1		113
-120			5	1	4	3			13
TOTAL	23	259	879	634	337	132	61	3	2328

TABLE VIII

F-105D ROLL RATE PEAKS vs MACH NUMBER

p	M (mach number)								TOTAL
	0.4	0.5	0.6	0.7	0.8	0.9	0.95	1.0	
120					2				2
90				9	7	3	1		20
60		4	24	40	45	13	3	2	131
30	7	48	183	382	275	85	17	12	1009
0									
-30									
-60	6	49	181	397	303	78	16	10	1040
-90	1	10	21	42	26	12		1	113
-120			1	5	4	3			13
TOTAL	14	111	410	875	662	194	3[illegible]	25	2328

TABLE IX

F-102A ROLL RATE PEAKS vs AIRSPEED for 0 - 2000 FT

p	Ve (equivalent airspeed)							TOTAL
	<250	250	300	350	400	450	500	
<0.52	413	67	82	271	29	82	790	1734
0.52	2	12	14	1	1		2	32
1.0								
1.5							1	1
2.0								
2.5	1	1	1					3
TOTAL	416	80	97	272	30	82	793	1770

TABLE X

F-102A ROLL RATE PEAKS vs AIRSPEED for 2000 FT

p	V_e (equivalent airspeed)								TOTAL
	<250	250	300	350	400	450	500	600	
<0.52				29	66	213	291		599
0.52		4	4	7	9	1	5	2	32
1.0		1		1				1	3
1.5		1							1
2.0									
2.5						1			1
TOTAL		6	4	37	75	215	296	3	636

TABLE XI

F-102 ROLL RATE PEAKS vs AIRSPEED for 5000 FT

p	Ve (equivalent airspeed)								TOTAL
	< 250	250	300	350	400	450	500	600	
< 0.52			47	243	260	17	11		578
0.52	1	11	35	13	9	5	21	6	101
1.0		6	9	2	2	2		1	22
1.5	1	1	2	1					5
2.0			2		1		3		6
2.5		1	6	1	1		1		10
TOTAL	2	19	101	260	273	24	36	7	722

TABLE XII

F-102A ROLL RATE PEAKS vs AIRSPEED for 15,000 FT

p	Ve (equivalent airspeed)						TOTAL
	< 250	250	300	350	400	450	
< 0.52			5			14	19
0.52	2	12	12	8	2		36
1.0	3	9	7	10			29
1.5		1	3	2			6
2.0				1			1
2.5	1	1	7	1		1	11
TOTAL	6	23	34	22	2	15	102

TABLE XIII

F-102A ROLL RATE PEAKS vs AIRSPEED for 25,000 FT

p	Ve (equivalent airspeed)				TOTAL
	< 250	250	300	350	
< 0.52				20	20
0.52	2	4	4	3	13
1.0		1			1
1.5		1			1
2.0			1		1
2.5			1		1
TOTAL	2	6	6	23	37

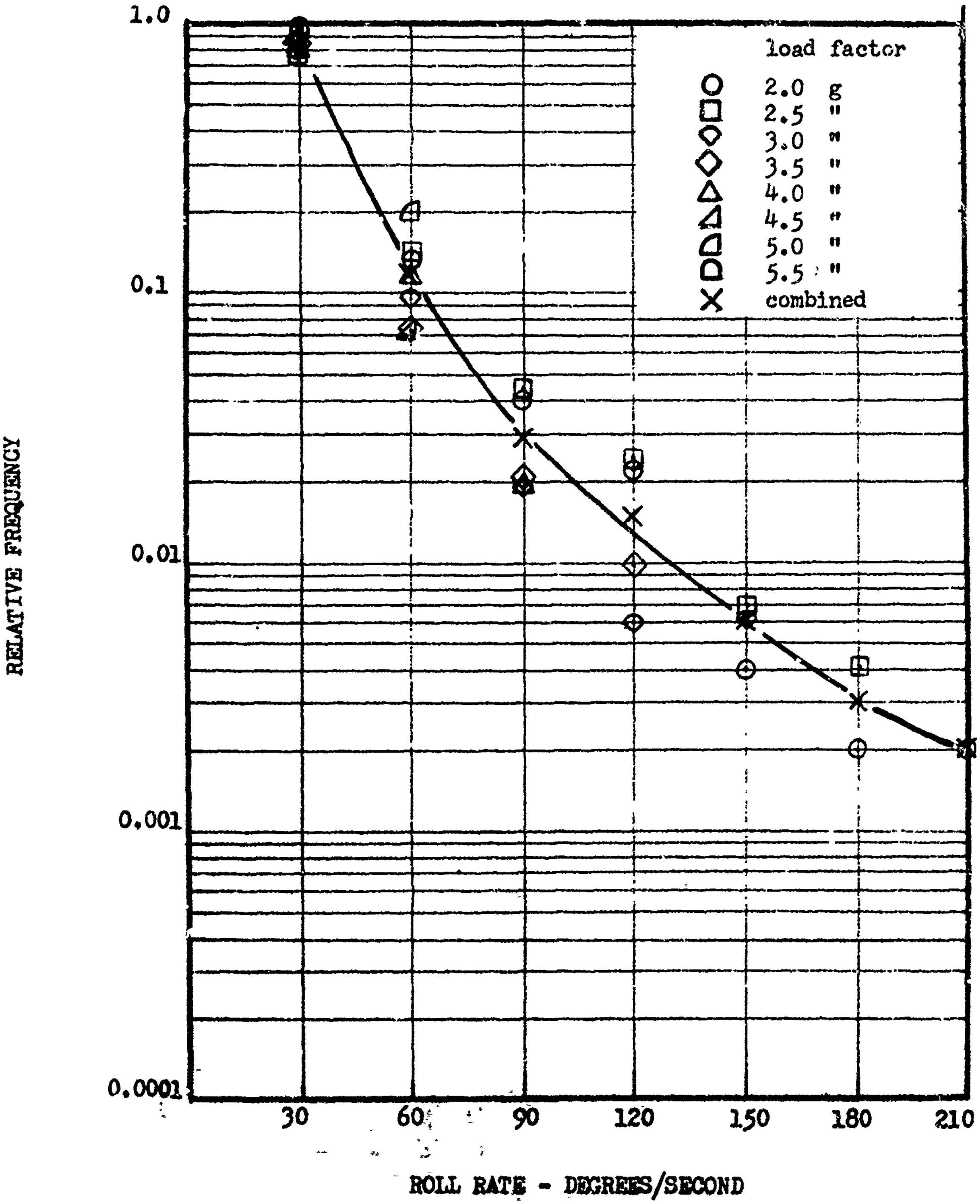

FIGURE 1 - RELATIVE FREQUENCY OF ROLL RATE PEAKS FOR THE F-5A

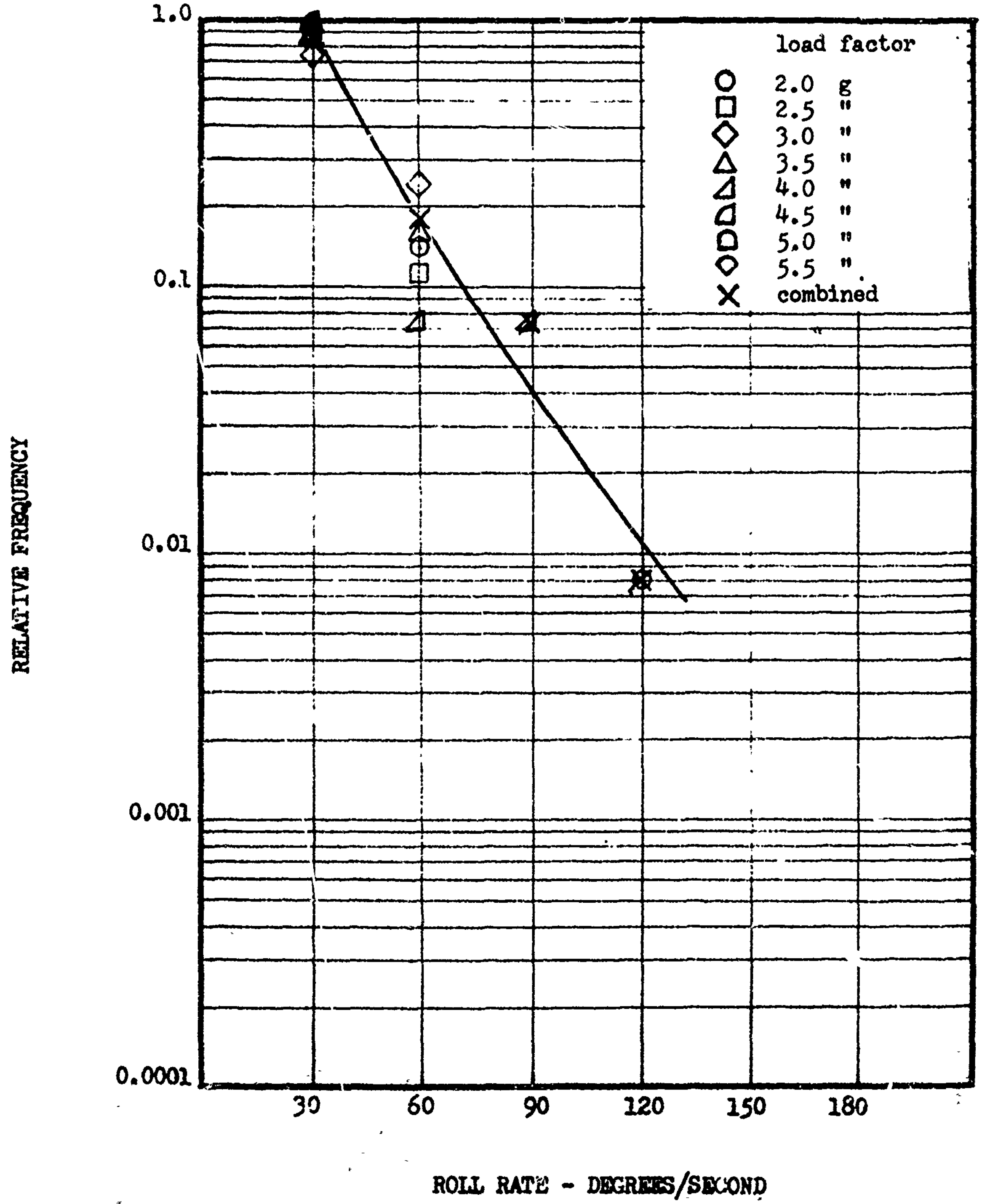

FIGURE 2 - RELATIVE FREQUENCY OF ROLL RATE PEAKS FOR THE F-105D

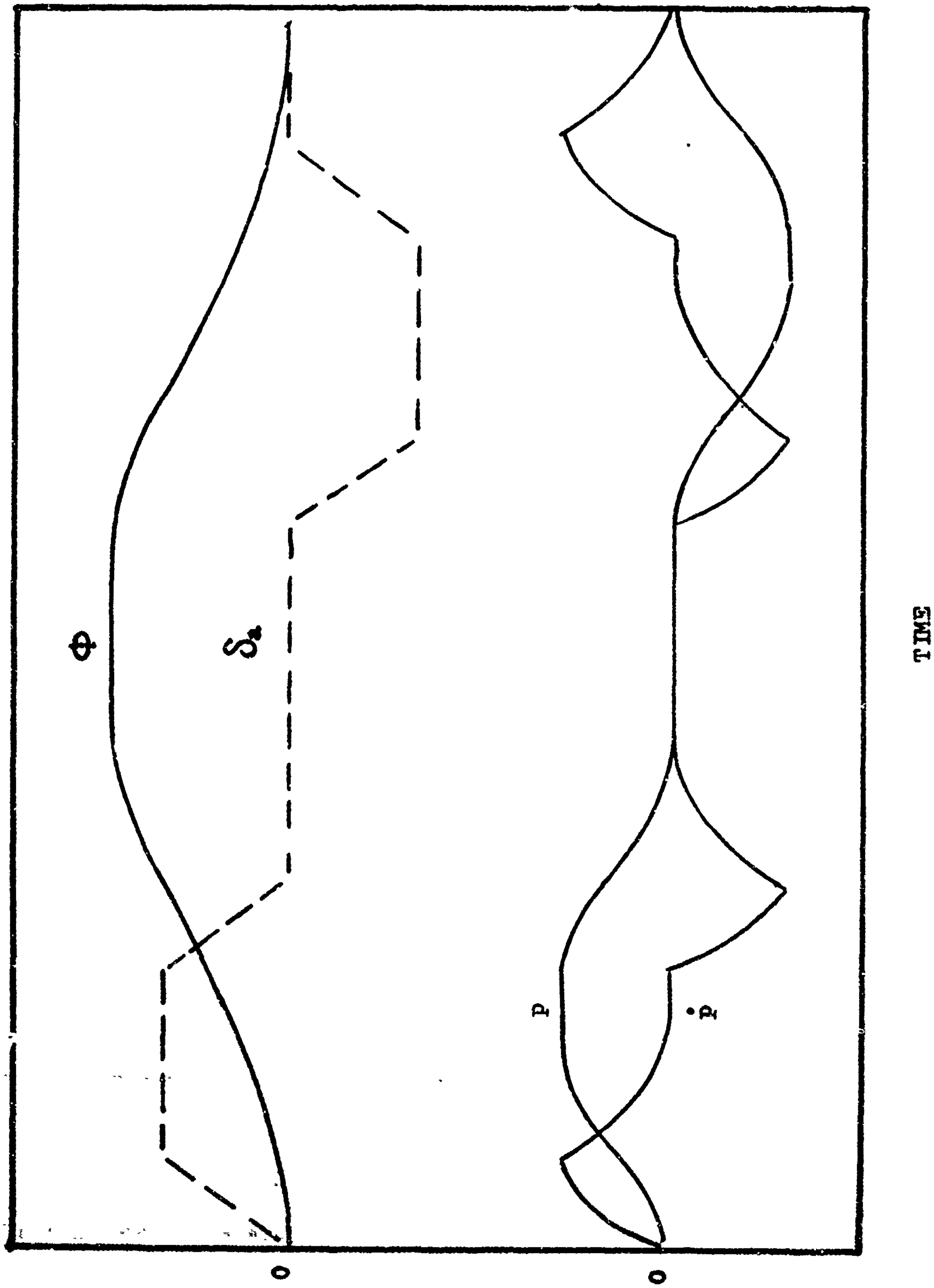

FIGURE 3 - SIMPLIFIED ROLLING MANEUVER TIME HISTORY

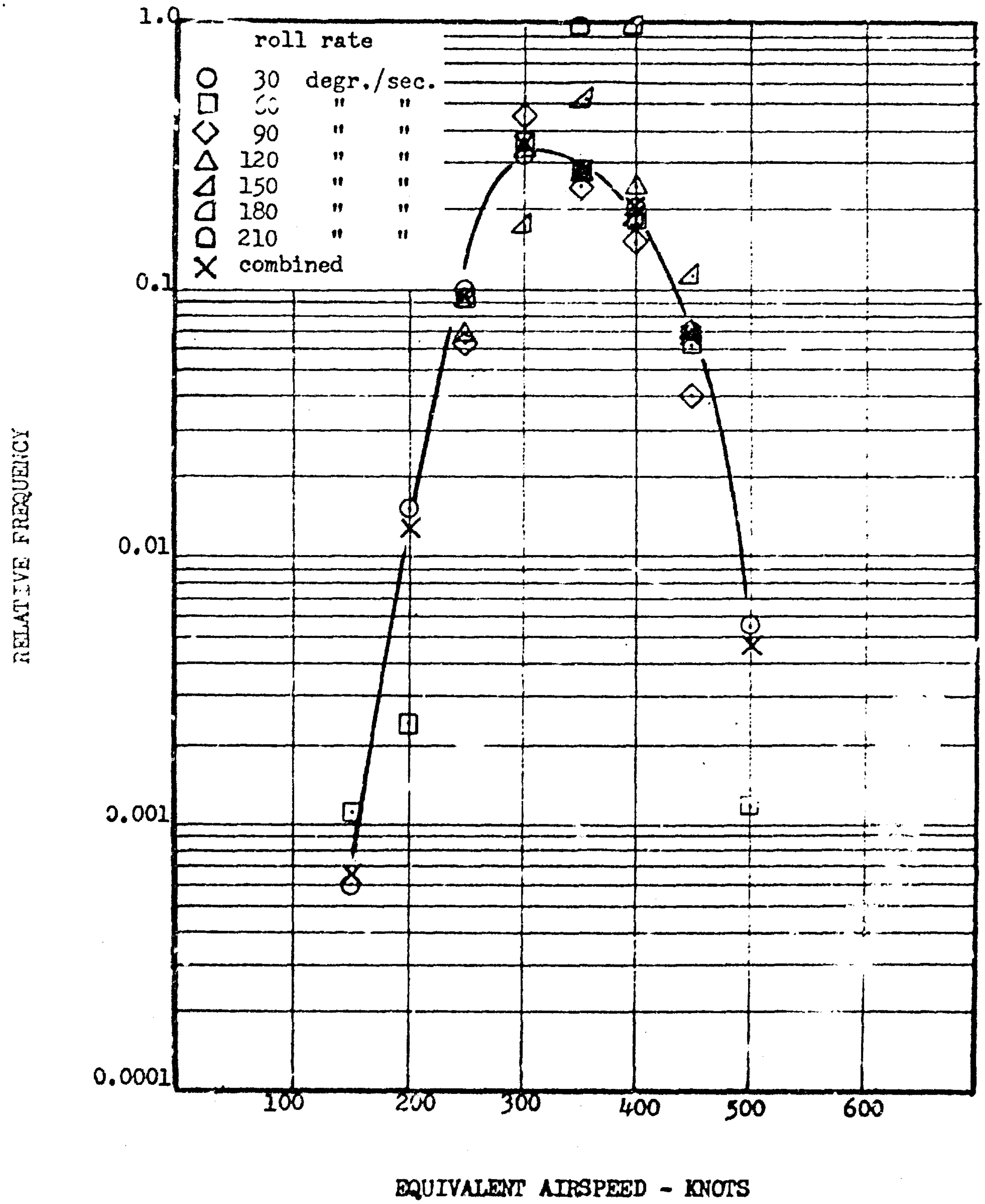

FIGURE 4 - RELATIVE FREQUENCY OF ROLL RATE PEAKS VS. AIRSPEED FOR THE F-5A

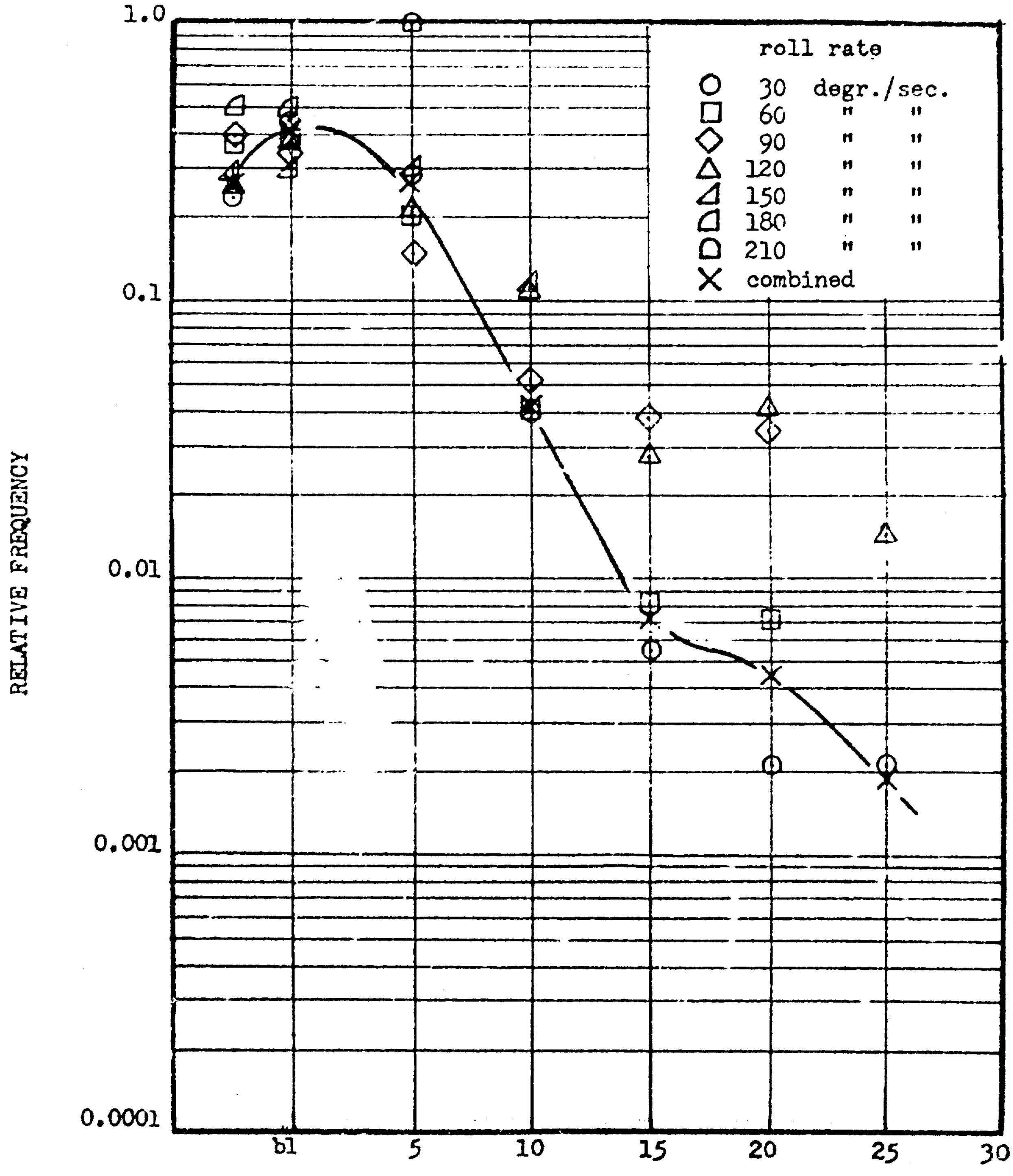

FIGURE 5 - RELATIVE FREQUENCY OF ROLL RATE PEAKS VS. ALTITUDE FOR THE F-5A

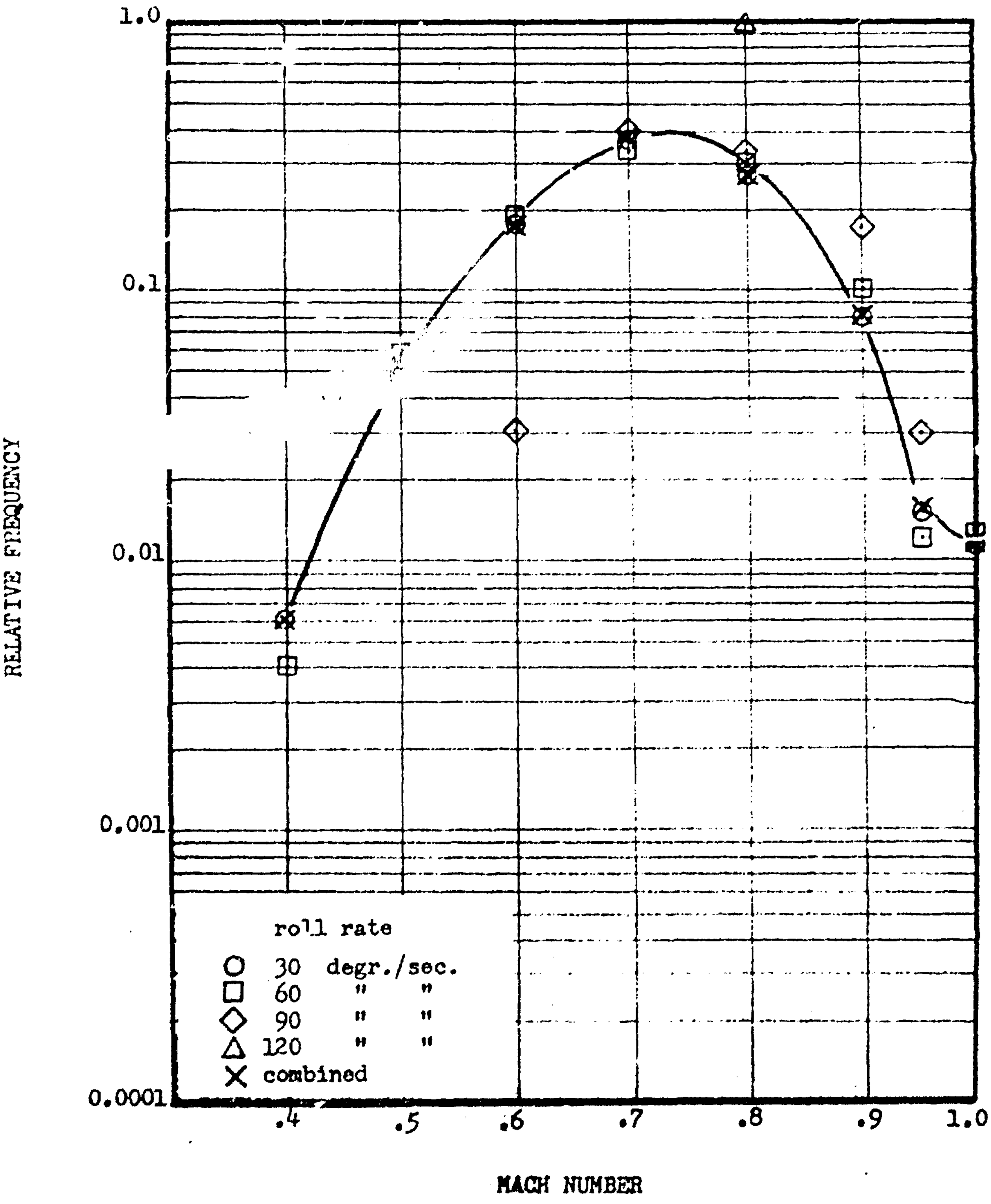

FIGURE 6 - RELATIVE FREQUENCY OF ROLL RATE PEAKS VS. MACH NUMBER FOR THE F-105D

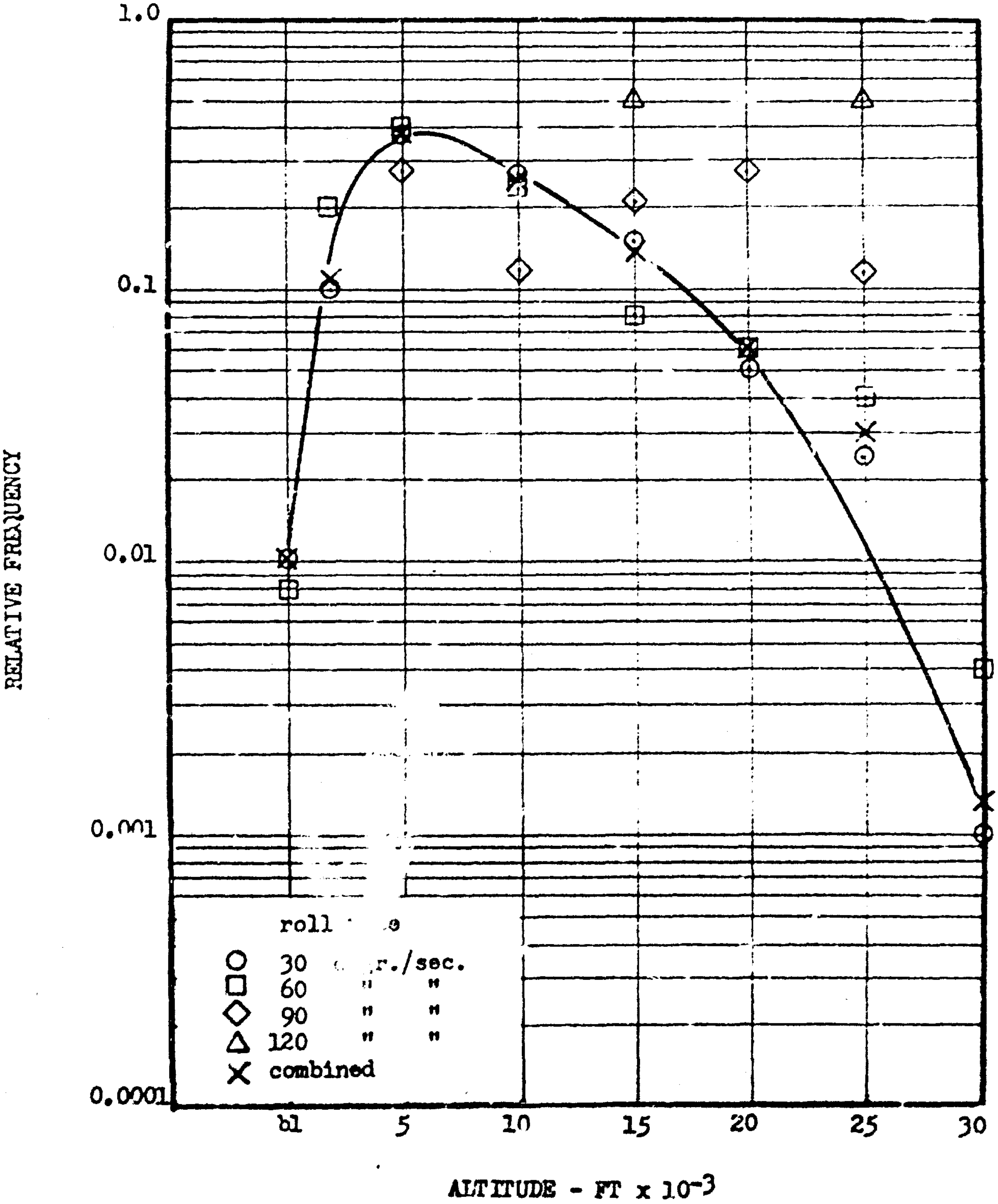

FIGURE 7 - RELATIVE FREQUENCY OF ROLL RATE PEAKS VS. ALTITUDE FOR THE F-105D

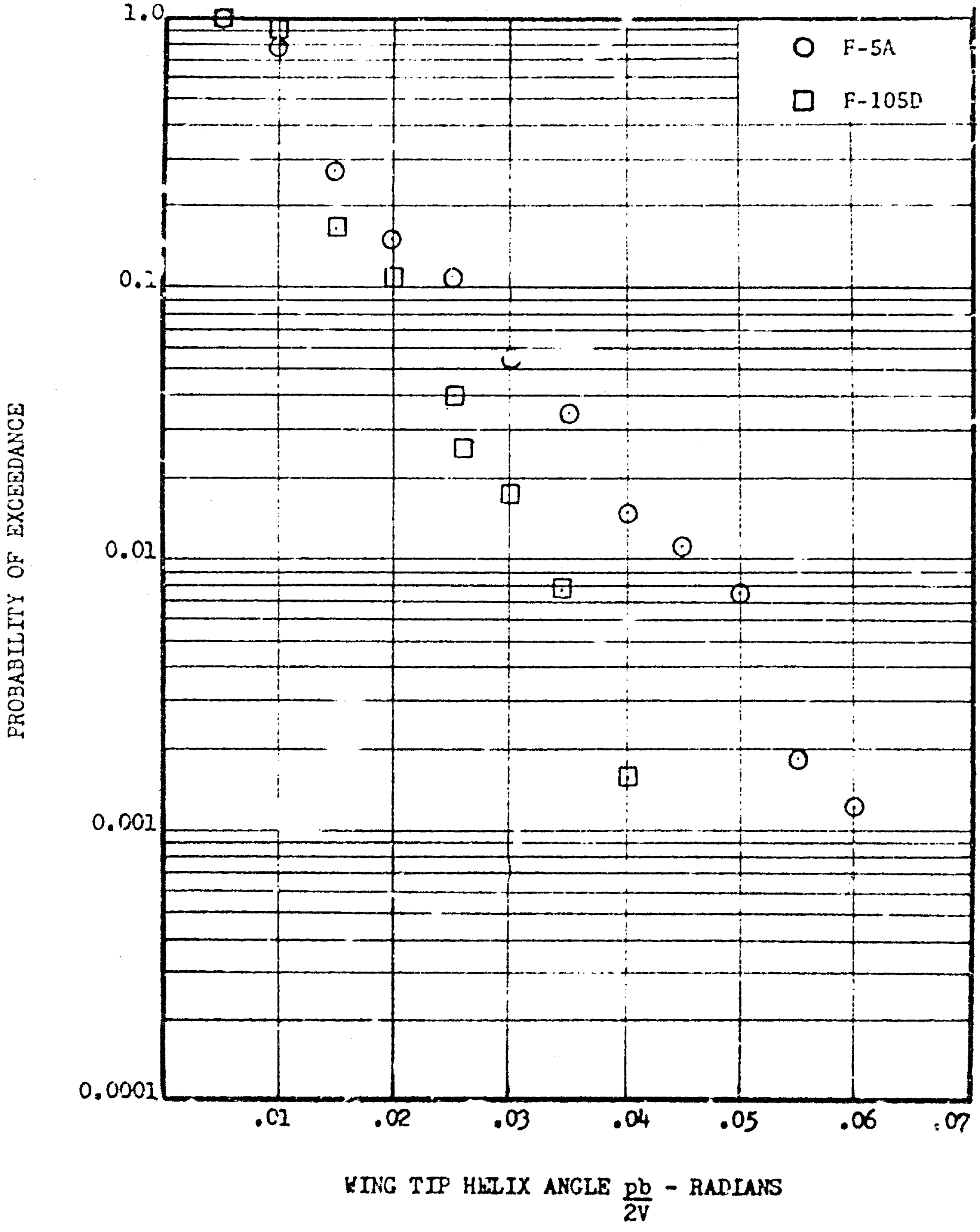

FIGURE 8 - PROBABILITY OF EXCEEDANCE OF THE WING TIP HELIX ANGLE FOR THE F-5A AND F-105D

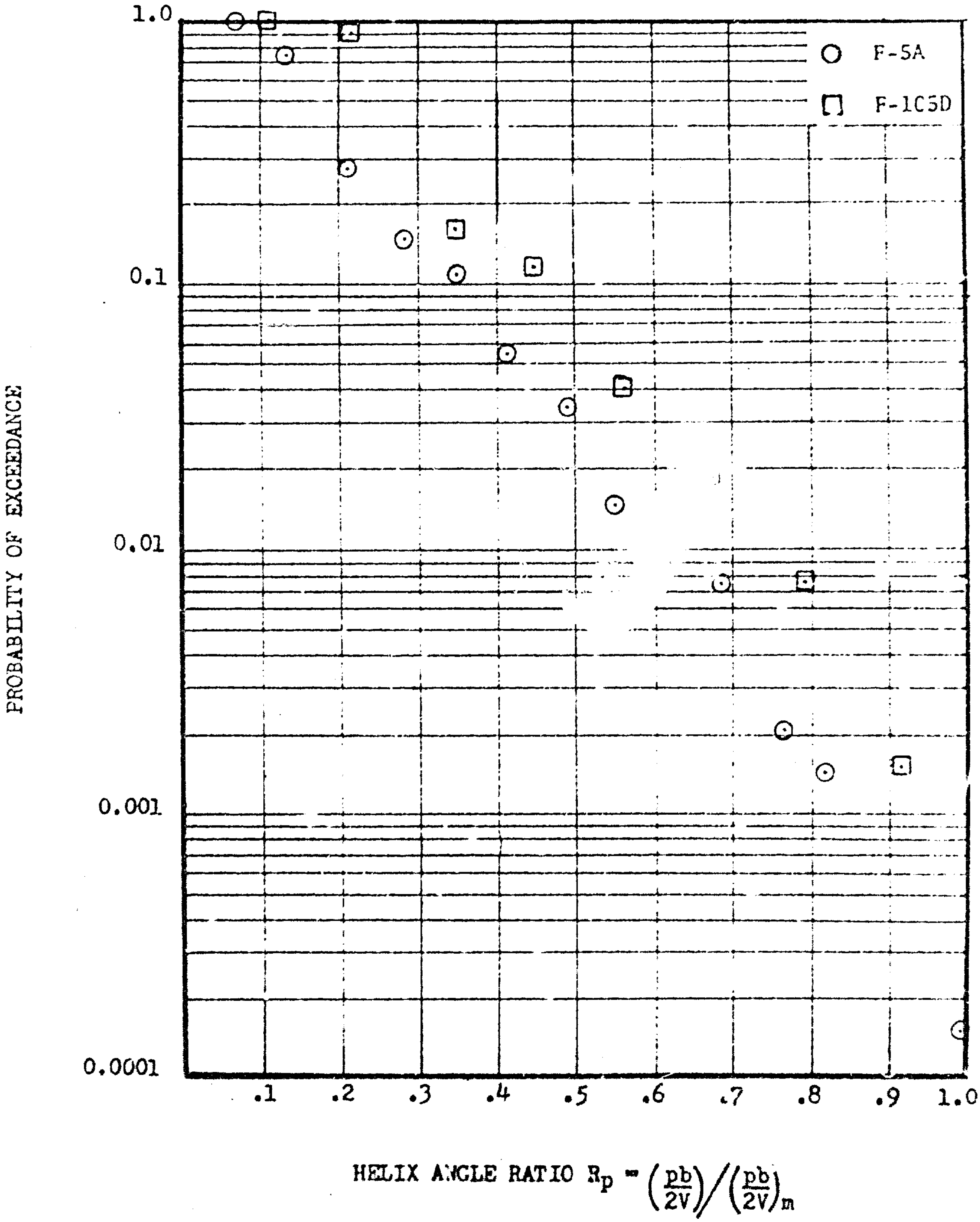

FIGURE 9 - PROBABILITY OF EXCEEDANCE OF THE NORMALIZED HELIX ANGLE

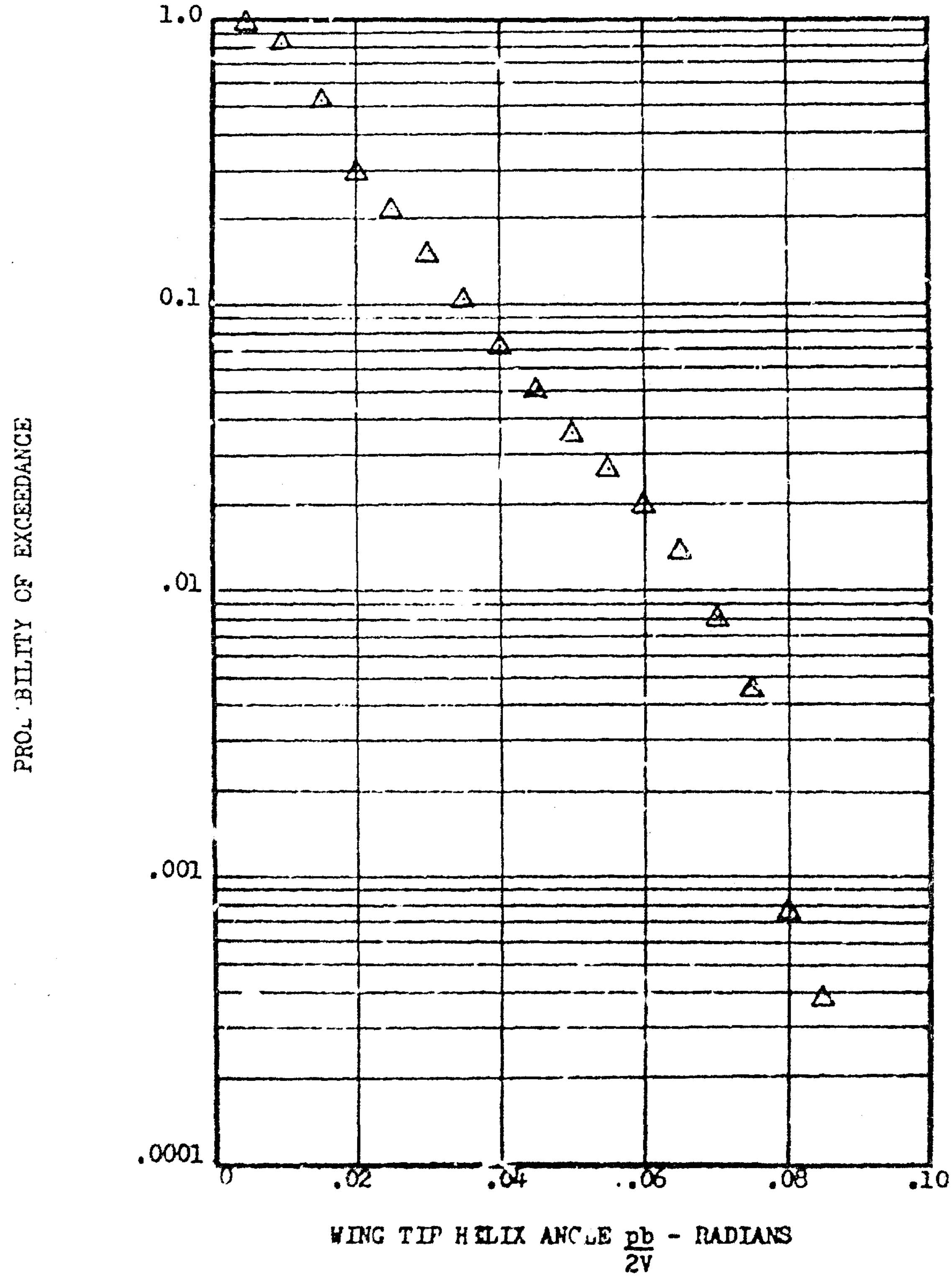

FIGURE 10 - PROBABILITY OF EXCEEDANCE OF THE WING TIP HELIX ANGLE FOR THE F-84F

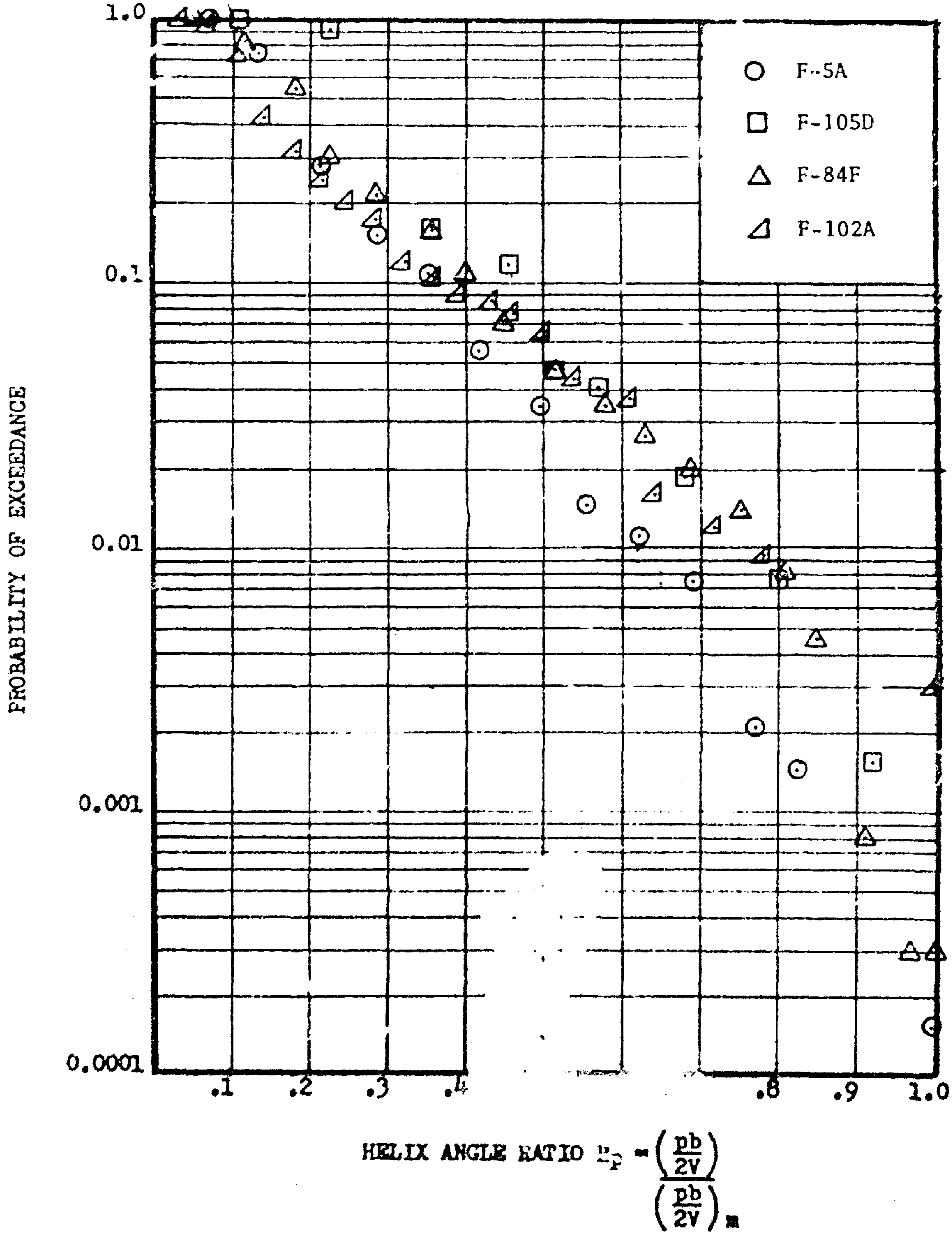

FIGURE 11 - PROBABILITY OF EXCEEDANCE OF HELIX ANGLE RATIO R_p FOR THE F-5A, F-105D, F-84F, AND F-102A

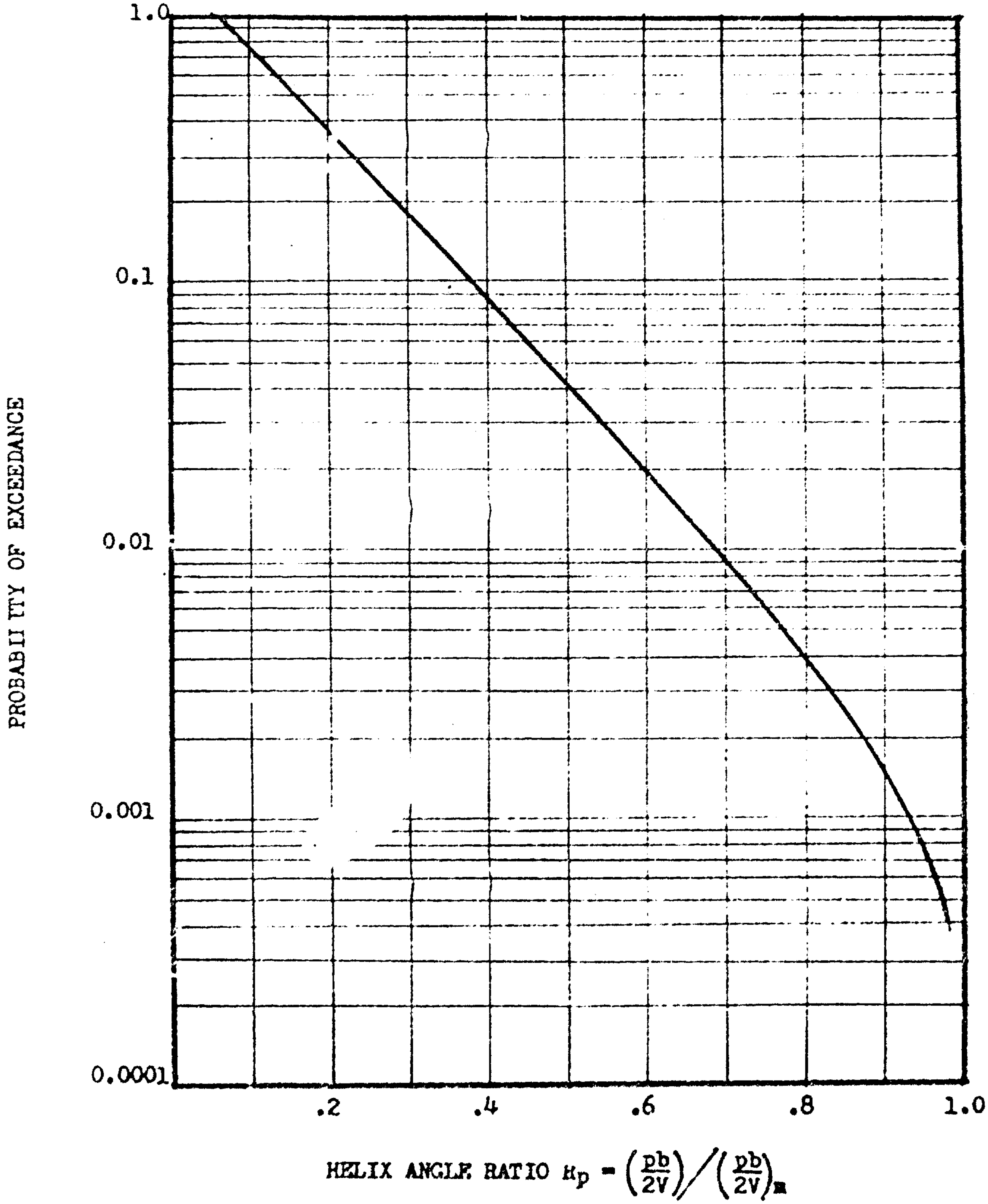

FIGURE 12 - PROBABILITY OF EXCEEDANCE OF THE HELIX ANGLE RATIO

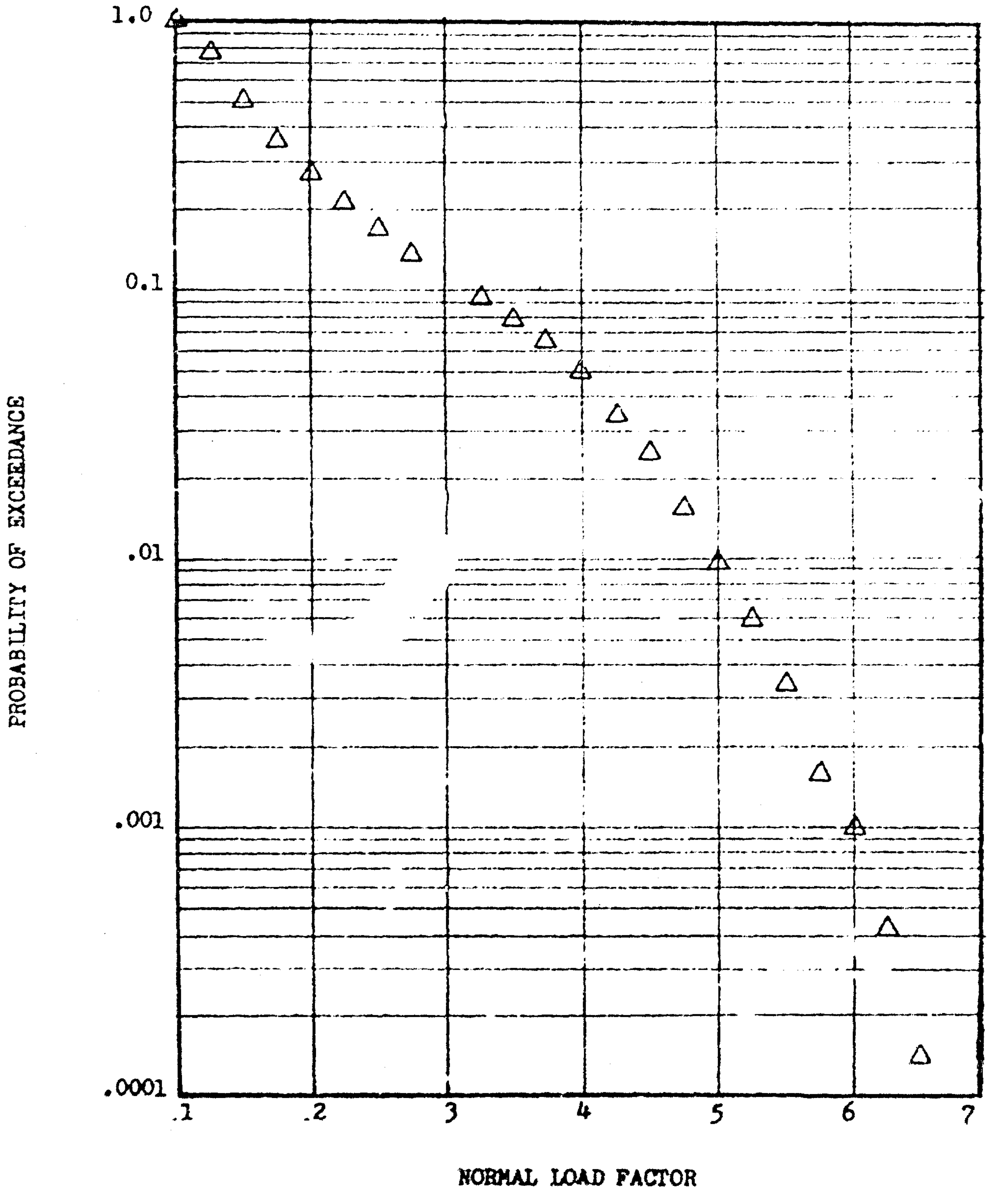

FIGURE 13 - PROBABILITY OF EXCEEDANCE OF THE POSITIVE NORMAL LOAD FACTOR FOR THE F-84F

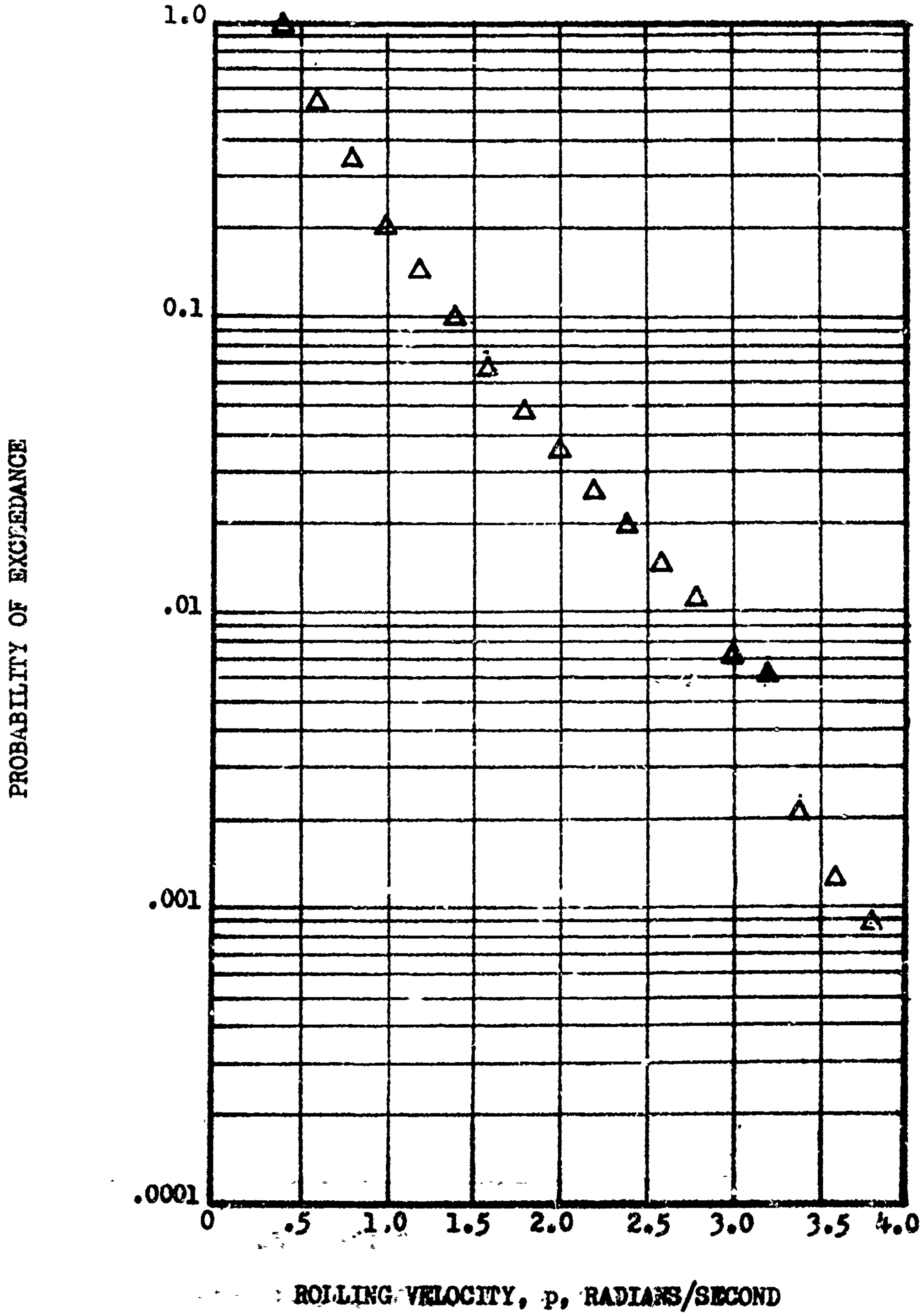

FIGURE 14 - PROBABILITY OF EXCEEDANCE OF THE ROLL RATE FOR THE F-84F

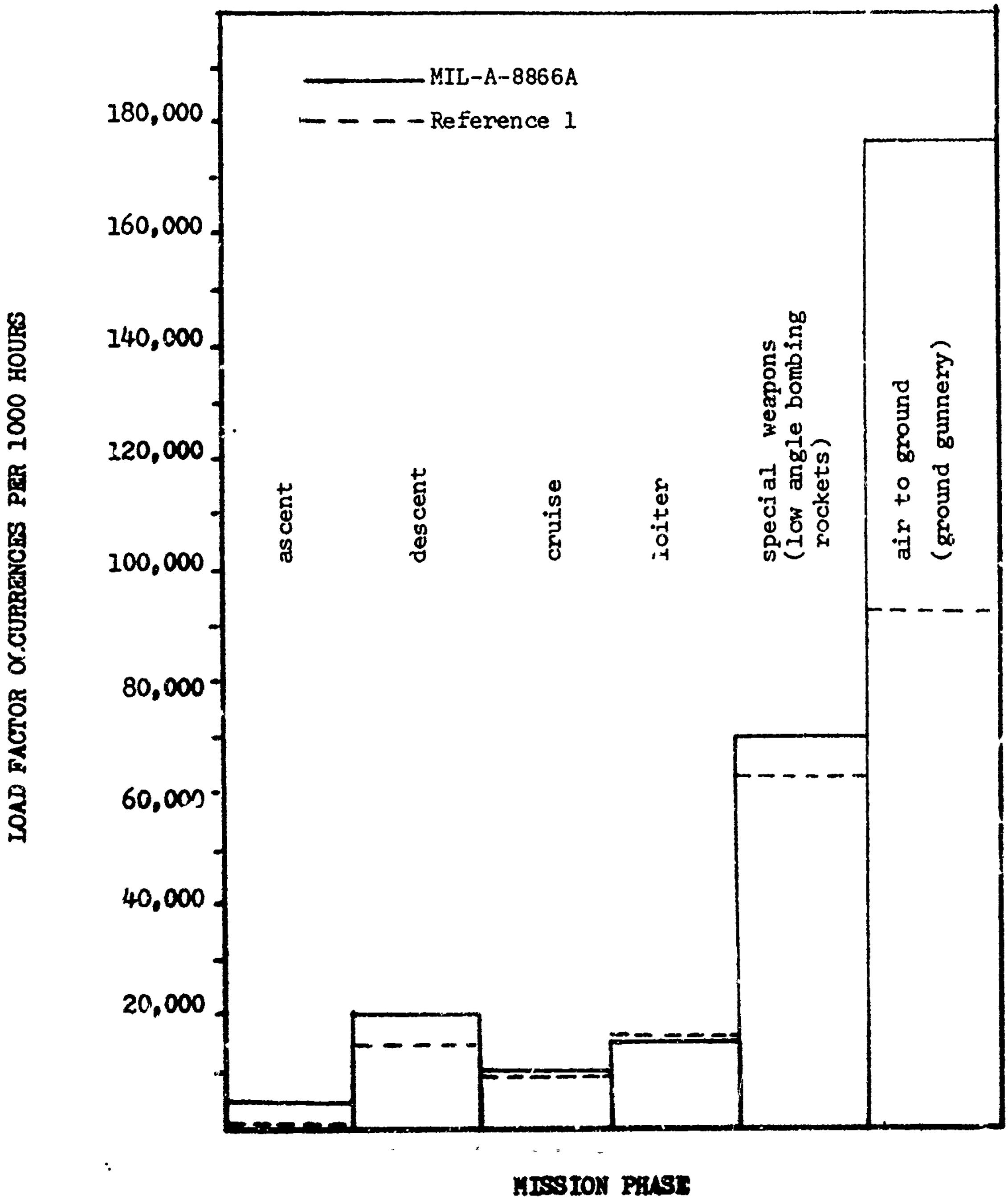

FIGURE 15 - COMPARISON OF LOAD FACTOR OCCURRENCES AS A FUNCTION OF MISSION PHASE