C.P. No. 574

C.P. No. 574

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Turbulence Encountered by Ambassador Aircraft over Europe

by

J. R. Heath-Smith, B.Sc. (Eng.)

LONDON: HER MAJESTY'S STATIONERY OFFICE

1961

PRICE 2s. 6d NET

U.D.C. No. 551.551(4) : 533.6.48.5

C.P. No. 574

December, 1960

TURBULENCE ENCOUNTERED BY AMBASSADOR AIRCRAFT OVER EUROPE

by

J. R. Heath-Smith, B.Sc.(Eng)

SUMMARY

Counting accelerometer records were obtained during 200,000 miles of flying by Ambassador aircraft on European routes.

It is shown that the turbulence experienced was substantially reduced by avoiding action. The reduction factor due to avoidance is about 3 during climb and descent and as great as 10 during cruise.

There is some evidence that gusts greater than about 15 ft/sec generally occur more frequently upwards than downwards, particularly in bad weather conditions.

Previously issued as R.A.E. Technical Note No. Structures 291-A.R.C.22,667

LIST OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1 INTRODUCTION

A counting accelerometer was installed in an Ambassador (Elizabethan) aircraft of British European Airways and recordings were obtained during the period September 1954 to February 1956 of the vertical accelerations experienced in 200,000 miles of flying below 20,000 ft.

This note gives an estimate of the turbulence encountered and its variation with altitude and flying conditions.

2 INSTRUMENTATION

A counting accelerometer Mk.2 was installed near the centre of gravity of the aircraft. It recorded the number of times that each of a series of upward and downward accelerations was exceeded. At intervals of time an automatic observer recorded the counts, airspeed, altitude and time. The time interval was 11.93 minutes on average during the tests. The first and last records of each flight contained the take-off and landing accelerations respectively.

3 TEST CONDITIONS

The aircraft carrying the accelerometer was flown on normal services in Europe. About 700 flights were recorded, a few, about 10%, not completely.

The distribution of recording time throughout the year, shown in Fig.1, is rather uneven owing to periods of unserviceability of the instrument.

Tables 1 and 2 show the time spent at each speed and altitude during climb and descent and during cruise respectively. It is seen that a wide range of cruising altitudes was used; the range 6,000-17,000 ft was used fairly uniformly and contains more than 90% of the time at cruise.

4 DATA

The counts of acceleration in various altitude bands during climb and descent and during cruise are given in Table 3. The first and last records of each flight are excluded as they contain ground loads but the recording time is included in the flight plan (Table 1). The average time between take-off and the first automatic observation is half the recording interval and the initial interval is represented as such in the flight plan. The altitude for this interval is taken to be half the altitude at the first observation in flight, and the speed is assumed to be constant over the interval so that the recorded value can be taken as representative. Similar assumptions are made for the observations immediately before landing.

5 GUST ANALYSIS

The acceleration data were processed and converted to gust information by the methods described in Ref.1. The aircraft characteristics assumed are stated in Table 4 and representative acceleration/gust conversion factors are given in Table 5. The estimated gust counts are given in Table 6.

6 VARIATION OF GUST FREQUENCY WITH ALTITUDE

In Fig.2 the average distance between gusts exceeding 10 ft/sec E.A.S. is plotted on a logarithmic scale against altitude. There are two sets of observations corresponding to climb and descent and to cruise. The vertical bars through each point show the 95% confidence limits calculated by the methods of Ref.2. The broken line represents the best estimate previously published of average conditions on routes in Europe, East and West Africa and the Far East.

Above 5,000 ft the two curves are typical of the turbulence experienced when the pilot is able to choose cruising altitude from a wide range with the object of avoiding turbulent conditions. The turbulence encountered is less during cruise than during climb and descent because the pilot is able to take avoiding action during the cruise, either by a change in height or by small changes of course. Furthermore, contrary to general evidence[4] of a continuous decrease of turbulence with altitude up to about 30,000 ft, there is a progressive reduction in the slope of the present curves with a minimum value of turbulence at about 12,000 ft. These considerations indicate that cruising altitude was increased with worsening weather conditions.

The points numbered 1 to 4 were observed during climb and descent in all flying weather. This portion of the climb and descent curve represents therefore the average conditions encountered by the aircraft. These conditions are 2 to 3 times less turbulent than the previous general estimate but are in good agreement with measurements[3] from Viking aircraft on the same routes. It is considered that the similarity of the Viking and Ambassador measurements is due to the similarities of their flight plans. Both aircraft climbed at a moderate rate and cruised within a wide range of altitude at moderate speed and it is deduced that these features increase the pilots ability to avoid turbulence by change of altitude and, when there are visible indications of turbulence, by change of course. The present data indicate that for most of the mileage flown the reduction in turbulence achieved by avoidance was about 3:1 during climb and descent and about 10:1 during cruise.

Points 7 and 8 which were probably made under stand-off conditions are more severe than the average climb and descent experience and it seems likely that they were associated with bad weather.

7 VARIATION OF GUST FREQUENCY WITH GUST SPEED

Fig.3 shows the variation of gust frequency with gust speed at different altitudes and flight conditions. In most cases the number of gusts exceeding 20 ft/sec is small and therefore the slope at smaller gust speeds is extended for ease of comparison.

Up and down gusts exceed 10 ft/sec in substantially equal numbers, allowing for some bias in the zero setting of the instrument, but the data show that generally gusts exceeding 15 ft/sec are more frequent upwards than downwards. This is most pronounced in observation 6 which represents unusual turbulent conditions during climb and descent and suggests that the observed inequality of upward and downward gust speeds may be real and not introduced by unequal upward and downward response by the aircraft and pilot.

8 CONCLUSIONS

The moderate speeds and wide range of operating altitude of the Ambassador permits considerable avoidance of turbulence. Over most of the altitude range the turbulence met was thus reduced by a factor of about 3 during climb and descent and about 10 during cruise, compared with, for example, a jet transport.

Upward and downward gust speeds exceed 10 ft/sec in substantially equal numbers but exceed higher values more frequently upwards than downwards. There is some indication that this inequality is more pronounced in severe conditions of turbulence.

ACKNOWLEDGEMENT

Thanks are due to British European Airways for their assistance.

LIST OF REFERENCES

Ref. No.	Author	Title, etc.
1	Heath-Smith, J.R.	The estimation of atmospheric gust frequencies from counting accelerometer records using the Deuce computer. A.R.C. 20,921. October, 1958.
2	Bullen, N.I.	The sampling errors of atmospheric turbulence measurements. A.R.C. R. & M. 3063. May, 1956.
3	Heath-Smith, J.R.	Turbulence encountered by Viking aircraft over Europe. A.R.C. Current Paper No. 311. July, 1956.
4	Bullen, N.I.	The variation of gust frequency with gust velocity and altitude. A.R.C. Current Paper No. 324. October, 1956.

TABLE 1 - Recording time in minutes at each speed and altitude during climb and descent

I.A.S. knots	Altitude above sea level I.C.A.N. (× 1,000 ft)																			
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
100	125																				
110	244	24																			
120	423	226	119	30	42	48	24	36	48		36		24	12							
130	464	405	411	428	327	196	101	167	65	83	59	48	48	24	12	24	12				
140	244	345	482	405	309	464	315	339	214	167	131	190	119	143	83	59	95		12	12	
150	136	328	470	577	713	672	393	369	369	202	155	119	119	107	83	59	59				12
160	18	279	185	310	441	530	512	416	333	131	167	178	95	71	143	59	48	48			
170	65	285	321	208	488	655	589	518	393	393	428	297	238	214	83	83			12		
180	18	291	298	179	292	393	470	613	309	119	119	83	59	59	12		12				
190	12	83	137	101	42	42	59	36	59	24		24	12	12		12					
200		18	24	24	6				12					12							
210		6	6																		
220			6																		
Totals	1749	2290	2459	2262	2660	3000	2463	2494	1802	1119	1095	939	714	654	416	296	226	48	24	12	12

Total Time 26,734 mins.

TABLE 2 - Recording time in minutes at each speed and altitude during cruise

I.A.S. knots	Altitude above sea level I.C.A.N. (× 1,000 ft)																				
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
100																						
110	12	12		12						12												
120	24	24	24							48	12	12										
130	24	36	24					12	12	12				12		12	24					
140	12	48			36	24	24	59	48	71	214	24	119	83	24	131	119	12	24	48	71	
150		24	24	95	36	36	83	286	214	238	131	155	357	369	654	928	928	559	155	95	59	12
160		12	12	83	155	143	309	416	821	964	750	726	1606	1725	964	714	1309	631	178	48	12	36
170		36	119	202	107	167	833	1154	1951	2035	1380	916	1083	750	988	416	333	36	12	48		
180			59	143	369	178	821	1011	1059	726	428	274	274	155	95	95	24					
190				12		12	59	59	12	12												
200					12																	
Totals	72	192	262	547	715	560	2129	2998	4117	4118	2915	2107	3439	3094	2725	2296	2737	1238	369	239	142	48

Total Time = 37,059 mins.

TABLE 3

Summary of accelerations recorded

Flight condition	Altitude range ft.	Recording time mins.	Statute miles	Number of times each acceleration increment was exceeded (+ Up, - Down)																	
				-1.02 g	-0.92 g	-0.82 g	-0.72 g	-0.62 g	-0.52 g	-0.43 g	-0.33 g	-0.23 g	0.23 g	0.33 g	0.43 g	0.52 g	0.62 g	0.72 g	0.82 g	0.92 g	1.02 g	1.12 g
Climb and descent (excluding first and last intervals of each flight)	0 - 1,500	59	160								2	12	26	3	1							
	1,500 - 3,500	2011	5953					6	8	20	71	311	559	158	50	20	8	4	2	1		
	3,500 - 5,500	4914	15820						3	24	133	650	887	280	59	10	3					
	5,500 - 9,500	7794	26780				1	3	6	18	123	507	688	228	52	15	5					
	9,500 - 13,500	3403	12299		1	2	3	6	14	26	75	189	213	92	38	15	7	1	1			
	13,500 - 17,500	988	3679			1	2	2	8	11	39	98	119	53	26	9	3					
	17,500 - 21,500	48	184									0	0									
Cruise	0 - 1,500	262	697						1	7	57	206	260	93	31	15	3	2				
	1,500 - 3,500	809	2668				1	2	10	21	88	229	490	188	51	19	1	1				
	3,500 - 5,500	1273	4434						4	11	40	104	177	70	27	11	4	1	1			
	5,500 - 9,500	13362	48709				3	8	17	39	123	444	532	180	51	21	5	3	1	1	1	1
	9,500 - 13,500	11554	43326					3	5	9	29	102	124	35	8	4	2					
	13,500 - 17,500	8995	34600					1	5	16	34	128	158	56	14	8	2	1				
	17,500 - 21,500	797	3147									0	0									

Total 202,456 miles.

TABLE 4

Aircraft characteristics assumed

Wing area	1,200 sq ft.
Aspect ratio	11.
Mean chord	10.46 ft.

Lift slope constant at 4.84 per radian.

TABLE 5

Acceleration/gust conversion factors

Values of the conversion factor in ft/sec/g are given below at some speeds and weights at sea level. The value decreases with increasing altitude and is about 6% smaller at 10,000 ft.

Indicated airspeed knots	Weight of aircraft (× 1,000 lb		
	40	45	50
100	49.66	54.25	58.64
120	41.38	45.21	48.87
140	35.47	38.75	41.89
160	31.04	33.91	36.65
180	27.59	30.14	32.58
200	24.83	27.12	29.32
220	22.57	24.66	26.66

TABLE 6 - Summary of estimated gust speeds

Flight condition	Altitude range ft	Mean altitude ft	Recording time min.	Statute miles	Number of times each gust speed was exceeded Vertical gust speed in ft/sec E.A.S. (+ Up, - Down)													
					-35	-30	-25	-20	-15	-10	10	15	20	25	30	35	40	45
Climb and descent (excluding first and last intervals of each flight)	0 - 1,500	1,000	59	160					2	14	16	3	1					
	1,500 - 3,500	2,600	2,011	5,953			2	9	24	160	310	66	17	6	1			
	3,500 - 5,500	4,500	4,914	15,820				2	26	310	580	53	17	1				
	5,500 - 9,500	7,200	7,794	26,780				4	27	220	370	57	9	1				
	9,500 - 13,500	11,300	3,403	12,299		1	3	8	27	98	120	32	7	2	1			
	13,500 - 17,500	14,900	988	3,679		1	2	4	15	72	92	37	10	1				
	17,500 - 21,500	18,800	48	184						0	0							
	21,500 - 25,500	23,500	24	110						0	0							
Cruise	0 - 1,500	500	262	697				1	19	190	200	50	15	6	2	1		
	1,500 - 3,500	2,700	809	2,668			1	3	22	130	230	45	7	1				
	3,500 - 5,500	4,400	1,273	4,434				1	5	55	80	19	3					
	5,500 - 9,500	7,700	13,362	48,709			3	13	41	170	260	47	9	3	2	1	1	
	9,500 - 13,500	11,600	11,554	43,326			1	3	9	41	56	7						
	13,500 - 17,500	15,300	8,995	34,600				2	10	53	84	15	3					
	17,500 - 21,500	18,800	797	3,147						0	0							

Total 202,456 miles.

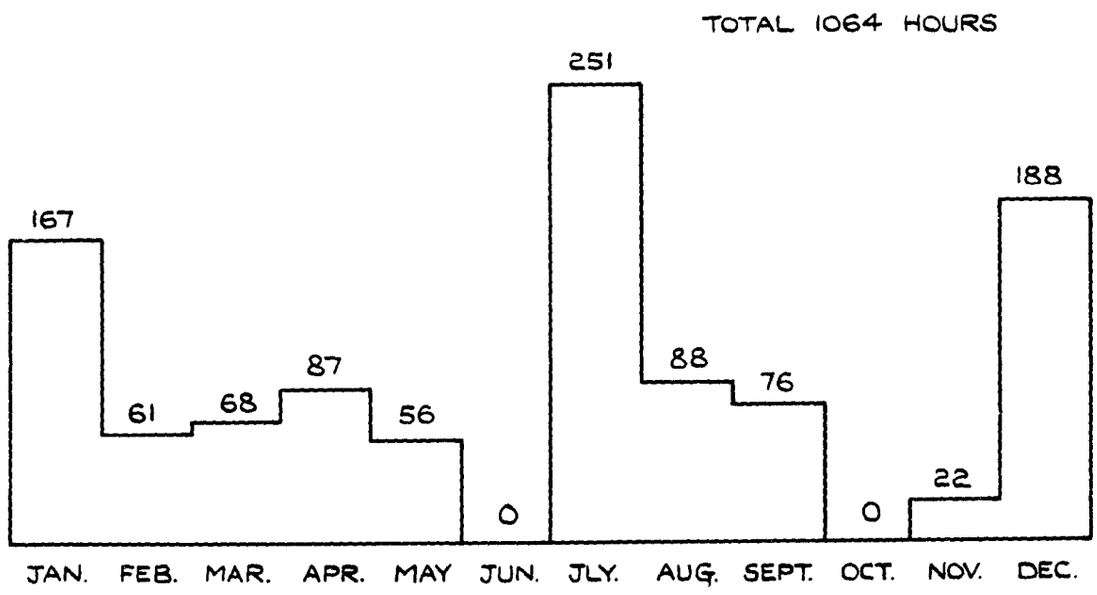

FIG. I. MONTHLY DISTRIBUTION OF RECORDING TIME.

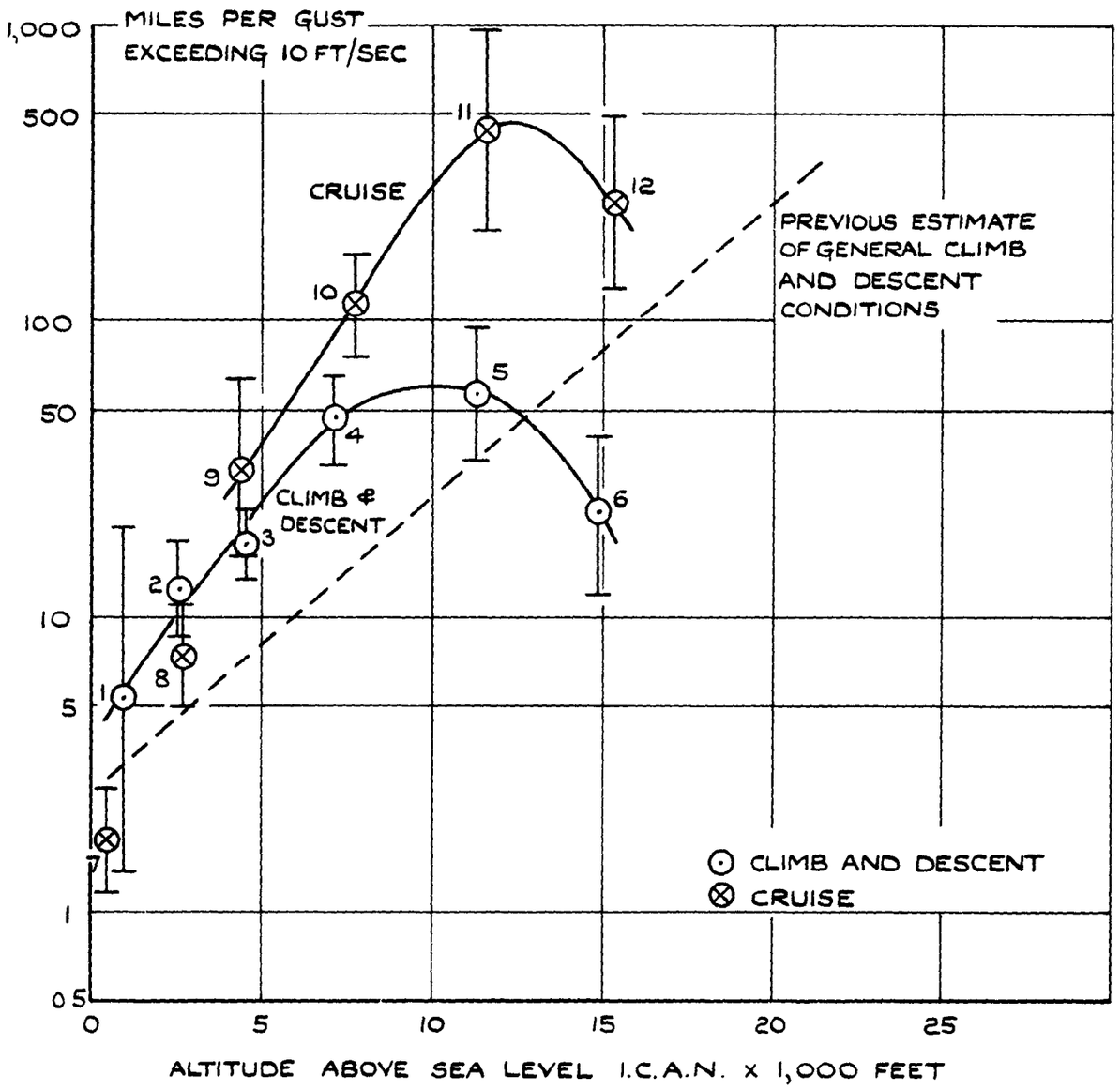

FIG. 2. VARIATION OF 10 FT/SEC GUST FREQUENCY WITH ALTITUDE.

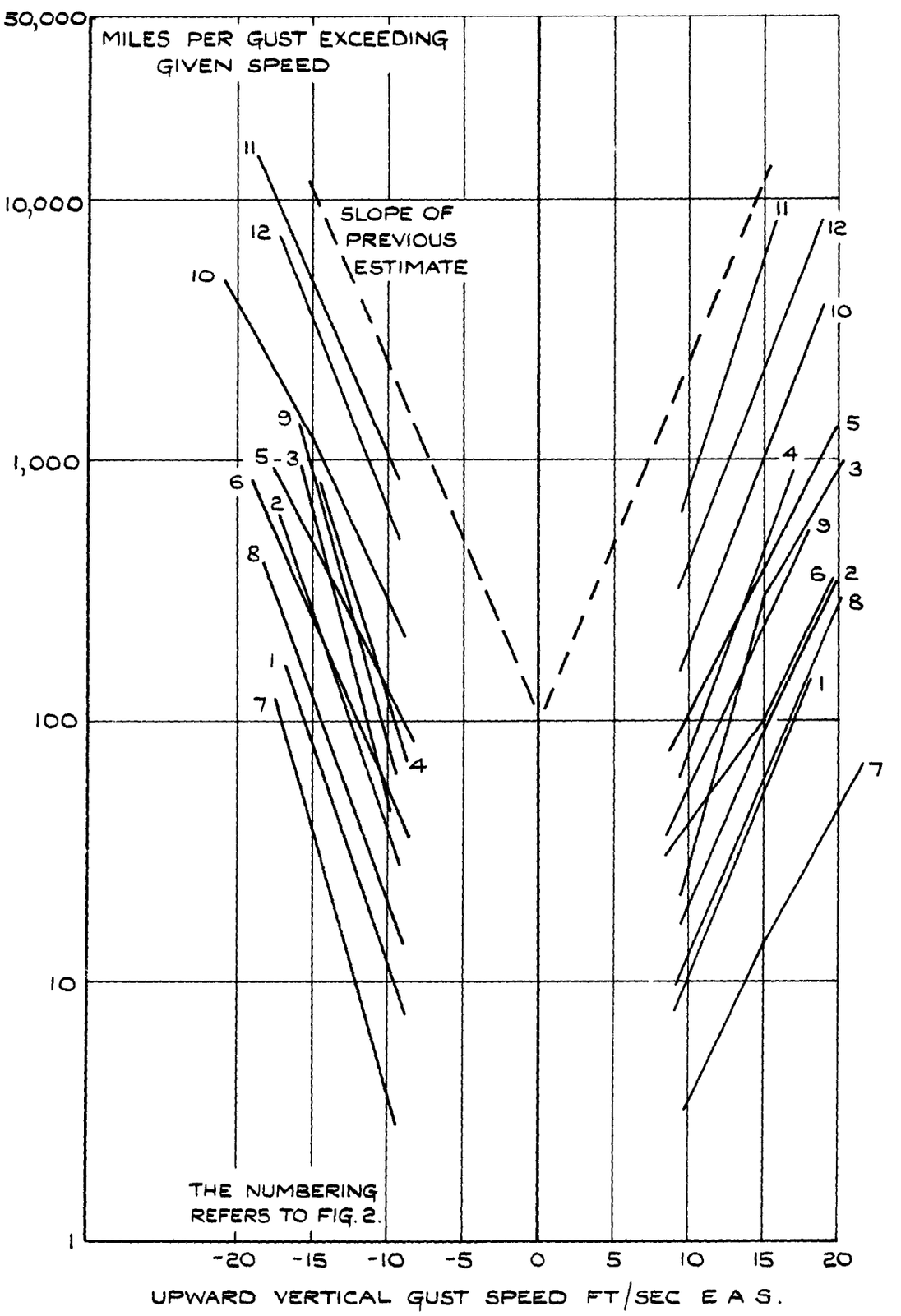

FIG. 3. VARIATION OF GUST FREQUENCY WITH GUST SPEED.

A.R.C. C.P. No. 574

551.551(4):
533.6.48.5

TURBULENCE ENCOUNTERED BY AMBASSADOR AIRCRAFT OVER EUROPE.
Heath-Smith, J.R. December, 1960.

Counting accelerometer records were obtained during 200,000 miles of flying by Ambassador aircraft on European routes.

It is shown that the turbulence experienced was substantially reduced by avoiding action. The reduction factor due to avoidance is about 3 during climb and descent and as great as 10 during cruise.

There is some evidence that gusts greater than about 15 ft/sec generally occur more frequently upwards than downwards, particularly in bad weather conditions.

A.R.C. C.P. No. 574

551.551(4):
533.6.48.5

TURBULENCE ENCOUNTERED BY AMBASSADOR AIRCRAFT OVER EUROPE.
Heath-Smith, J.R. December, 1960.

Counting accelerometer records were obtained during 200,000 miles of flying by Ambassador aircraft on European routes.

It is shown that the turbulence experienced was substantially reduced by avoiding action. The reduction factor due to avoidance is about 3 during climb and descent and as great as 10 during cruise.

There is some evidence that gusts greater than about 15 ft/sec generally occur more frequently upwards than downwards, particularly in bad weather conditions.

A.R.C. C.P. No. 574

551.551(4):
533.6.48.5

TURBULENCE ENCOUNTERED BY AMBASSADOR AIRCRAFT OVER EUROPE.
Heath-Smith, J.R. December, 1960.

Counting accelerometer records were obtained during 200,000 miles of flying by Ambassador aircraft on European routes.

It is shown that the turbulence experienced was substantially reduced by avoiding action. The reduction factor due to avoidance is about 3 during climb and descent and as great as 10 during cruise.

There is some evidence that gusts greater than about 15 ft/sec generally occur more frequently upwards than downwards, particularly in bad weather conditions.

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London W.C.2
423 Oxford Street, London W.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
50 Fairfax Street, Bristol 1
2 Edmund Street, Birmingham 3
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

S.O. CODE No.23-9012-74