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Turbulence Encountered by Viking Aircraft over Europe

By

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

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Turbulence encountered by Viking aircraft over Europe

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

SUMMARY

Accelerations in turbulence were recorded on B.E.A. Viking aircraft for 117,000 miles of flying over European routes during three years.

The records show that the number of gusts decreases from sea level to 8000 feet. There is some evidence below 5000 feet that turbulence is greatest in Spring and least in Autumn.

Average gust frequencies during climb and descent were twice those during cruise below 8000 feet and this is attributed to the pilot's discretion in the choice of cruising altitude.

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1 Introduction

From November 1951 to November 1954 a Counting Accelerometer was carried in a Viking aircraft of British European Airways, which was operated on normal passenger service over Europe. The records obtained represent 117,000 miles of flight below 10,000 feet.

The data are examined to determine the variation in turbulence with altitude and with season.

2 Description of Equipment and Flying

2.1 Instrument and Installation

The Counting Accelerometer[1] responds to the accelerations imposed on it along one axis and records the number of times each of a series of acceleration levels has been exceeded. Successive counters represent levels at intervals of 0.1g and readings are given for a range of 1.2g to 2.9g for upward accelerations and from 0.8g to -0.9g for downward accelerations. The above values are nominal and have been corrected in this report except where it is stated otherwise. An altimeter, airspeed indicator and spring-driven clock are grouped around the counter dial and the whole assembly is photographed at regular intervals of approximately 10 minutes.

The Counting Accelerometer was rigidly attached to the airframe in the forward luggage compartment about three feet ahead of the centre of gravity of the aircraft and in such an attitude that vertical accelerations were measured when the aircraft was in cruising flight.

2.2 The flying covered by the records

The records were obtained between November 1951 and November 1954 on 350 flights covering 117,000 miles of operational flying on European routes based on London. The distribution of recording time between months of the year is shown in Fig 1. The instrument was carried at different times in Viking aircraft G-AIVH and G-AMGJ.

3 Variation in turbulence with altitude

The recording intervals are of average duration 10.5 minutes and contain the total counts of acceleration during this interval and the speed and height of the aircraft at the end of this interval. Appendix I describes various corrections which are made to these readings and the method of translating the accelerations into gust speeds.

Table I is a summary of the time spent at each speed and altitude during climb, cruise and descent. Table II is a summary of the counts of acceleration grouped according to speed, weight and altitude. Table III is an estimate of the gust speeds encountered in each altitude band during climb, cruise and descent. As the climb and descent gust frequencies are similar they are shown separately and combined.

Fig 2 shows the gust frequencies in each altitude band for cruise and for climb and descent. Fig 3 shows directly the variation with altitude of the frequency of gusts greater than 10, 15 and 20 ft/sec for cruise and for climb and descent. The form of these curves and the difference between cruise and combined climb and descent suggests that the operating conditions and flight plan of the Viking influenced the recorded gust frequencies.

There is evidence in the records from Comet aircraft[4] that gust frequency decreases exponentially with altitude up to about 25,000 ft. This result is practically free from selective recording as the aircraft climbed and descended through this range to a strictly observed flight plan. It is assumed therefore that yearly average turbulence over Europe decreases exponentially with altitude within the altitude range of the Viking and this turbulence is referred to hereafter as atmospheric turbulence to distinguish it from recorded turbulence. As the Comet spectrum refers to world-wide routes it is not used directly for comparison with the Viking recorded turbulence.

There are two ways in which recorded turbulence is influenced by the pilot of the aircraft. Under nearly all conditions of flight the pilot takes sideways avoiding action to some extent when faced with bad weather and for this reason recorded turbulence will be less than atmospheric turbulence at all altitudes. In addition the average flight plan in Table I suggests that the pilot was allowed considerable discretion in the choice of cruising altitude, as the aircraft cruised over a wide range of altitude being limited to 10,000 feet as the cabin was unpressurized. The pilot's choice would be influenced to a great extent by weather conditions; the general result would be the selection of low altitudes during calm weather and of high altitudes during rough weather.

It follows that the gust frequencies recorded during cruise would be less than the atmospheric average at the lowest altitudes and greater than the atmospheric average at the highest altitudes, because flight at the highest altitudes would be made only when the weather was rough and flight at the lowest altitudes would be made only during calm weather. Similarly gust frequencies recorded during climb and descent would be the atmospheric average near sea level and progressively greater than atmospheric average with increasing altitude because the climb to the highest altitudes would be made only in rough weather.

In fact, these effects can be seen in Fig 3 in the curvature and relative position of the cruise curve and climb and descent curve. In the lowest altitude band the same degree of turbulence was recorded in descent and cruise from which it is deduced that altitudes below about 2000 feet were maintained only for landing approaches and circuits.

It has been assumed that atmospheric gust frequency can be represented by a straight line in Fig 3, and its position can be estimated by continuing the low altitude portion of the climb and descent curve as a straight line, shown as a broken line in Fig.3 for gusts greater than 10 ft/sec. This line intercepts the cruise curve in the region of minimum recorded gust frequency which also corresponds approximately with the most usual cruising altitude.

4 Seasonal variation of turbulence

The records best suited to a study of seasonal variation of turbulence are those made at low altitude during climb and descent as they are representative of all weather conditions.

A summary of the 10 ft/sec gust counts and mileages in each month for the altitude range 1500 to 5500 feet are given in Table IV. The turbulence for each month is expressed as the ratio of the average number of gusts per mile in that month to the average number of gusts per mile during the year. The yearly average is the weighted mean of the monthly averages. Turbulence ratio is plotted against month in Fig 4 and confidence limits are shown for each point within which there is 95% probability that the true average lies. In the estimation of these limits allowance is made for the tendency for gusts to be concentrated in regions[5]. The degree of concentration is estimated by comparing the average number of gusts in a recording interval with the proportion of intervals containing gusts greater than 10 ft/sec. This information is included in Table IV.

The confidence limits in Fig 4 suggest that the monthly sample size is too small for accurate assessment of the variation of turbulence between months but there is some indication that turbulence is greatest in Spring and least in Autumn. To assess the variation quantitatively two hypotheses are now examined using the χ^2 test for goodness of fit.

The first hypothesis is that all the observed variation is sampling error and that average monthly turbulence is constant. The result of this test is a probability of 10% ($\chi^2 = 17$, 11 degrees of freedom).

For the second hypothesis, visual inspection suggests a sinusoidal variation of goodness with a period of one year. If a sine curve is based on the mean annual turbulence with amplitude and phase adjusted to make χ^2 a minimum, the result is a probability of 15% ($\chi^2 = 13$, 9 degrees of freedom).

It appears that neither fit is good but the sine variation is nevertheless more probable than no variation on the present evidence. On the basis of the fitted sine curve the extreme variation in monthly turbulence is about 3 to 1.

5 Conclusions

There is a continuous decrease in gust frequency with increasing altitude from sea level to 8000 feet.

As a result of the pilot's choice of flight path with regard to weather conditions the average gust frequencies during climb and descent were twice as great as average gust frequencies during cruise, at altitudes below 8000 feet.

There is some evidence that turbulence below 5000 feet is greatest in Spring and least in Autumn and that the extreme monthly variation during the year is of the order of 3 to 1.

Acknowledgements

Thanks are due to the British European Airways Corporation for their co-operation in the installation and servicing of the instruments.

REFERENCES

No.	Author	Title, etc
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2	-	Air Publication 970, Chapter 203.
3	J. K. Zbrozek	Gust Alleviation Factors. R & M. 2970 - May, 1951.
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APPENDIX I

Description of acceleration data and gust analysis

The data consist of a series of consecutive records of average duration 10.5 minutes, containing the number of times each acceleration level was exceeded and the speed and altitude of the aircraft at the end of the interval. The speed is expressed to the nearest 10 knots I.A.S. and the altitude to the nearest 1000 feet above sea level.

Those records which may contain the effects of ground loads are discarded with the result that, on average, the first and last 5.25 minutes of each flight are not included in the analysis.

Those records in which the altitude change is greater than 1 unit (nominally 1000 feet) are classified as "climb" or "descent" and the altitude reading is corrected with due regard to the probable variation of gust frequency with altitude. The remaining records are classified as "Cruise". When the speed change during an interval is greater than 1 unit (nominally 10 knots) the mean speed is taken.

The records are sorted into the following altitude bands: 0-1500 feet, 1500-3500 feet, 3500-5500 feet, 5500-7500 feet, 7500-9500 feet and 9500-11500 feet.

The counts of acceleration are grouped and summarized according to the flight condition, altitude and speed of the aircraft.

Mean aircraft weights of 32,400 lb, 31,750 lb and 31,100 lb are calculated for the climb, cruise and descent from the take-off and landing weights known for each flight.

Accelerations are translated into gust speeds by the formula:

$$U = \frac{\Delta n \, w}{F \frac{1}{2} \rho_0 a V}$$

U	equivalent vertical gust speed
Δn	normal acceleration increment in g units
w	wing loading
F	gust alleviation factor*
ρ_0	air density at sea level (I.C.A.O.)
a	slope of the lift curve (low speed)
V	indicated airspeed

By graphical interpolation the counts are referred to gust speeds of 10, 15, 20, ... ft/sec and a gust speed distribution is obtained for each altitude band and flight condition. The mileage flown in each band is estimated and the gust distributions are obtained in terms of the average distance between gusts exceeding given magnitudes.

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* The gust is assumed to increase linearly to its maximum value in a horizontal distance of 100 feet. The alleviating factor is calculated as a function of the mass parameter $\mu g = 2w/g \rho \bar{c} a$ where ρ is air density and $\bar{c}$ is the mean aerodynamic chord. Allowance is made for the effect of aspect ratio on the rate of growth of lift. Compressibility effects are neglected.

TABLE I

Estimated time in minutes spent at each speed and altitude

Altitude above sea level (I.C.A.N.) in 1000's of feet

Climb

Indicated airspeed in knots	00	01	02	03	04	05	06	07	08	09
100										
110	5				5					
120	30	25	25	10		10				
130	160	245	235	120	80	65	40	20	20	40
140	130	390	270	230	200	145	190	55	30	40
150		40	120	115	230	265	220	200	30	40
160			20	75	105	125	85	20	10	
170				10	10	20	10			
180										
Total	325	700	670	560	630	630	545	295	90	120

Cruise

Indicated airspeed in knots	00	01	02	03	04	05	06	07	08	09	10	11
100												
110		10	10									
120	20	20	55	10		10			10	10	10	
130	20	65	115	230	135	95	65	105	190	200	170	20
140	10	115	315	250	315	335	715	945	1145	1280	600	135
150		135	355	420	380	1250	2165	2720	2835	2480	1105	170
160	20	180	370	390	495	1105	1910	1665	870	305	135	20
170		20	95	85	85	180	190	65	105	10	10	
180			10		10	10						
Total	70	545	1325	1385	1420	2985	5045	5500	5155	4285	2030	345

Descent

Indicated airspeed in knots	00	01	02	03	04	05	06	07	08	09	
100	105	25	10	10							100
110	215	135	20	20	10	10					110
120	145	290	210	110	5	30	10	10	10		120
130	120	295	355	115	65	65	30	20	10		130
140	5	150	195	260	170	160	65	65	30	40	140
150			145	135	190	220	210	200	65	40	150
160		10	105	85	145	220	190	180	95	40	160
170		20		65	160	200	105	75	20		170
180					20	20	20	10			180
Total	590	925	1010	800	765	925	630	560	230	120	

Climb: 4,565 mins. Cruise: 30,090 mins. Descent: 6,585 mins.

TABLE II

Summary of Acceleration Data from Viking Aircraft

Flight Condition	Altitude above sea level feet	Indicated airspeed knots	Recording Time (10.5 min units)	Number of times each level of acceleration was exceeded Nominal Acceleration-Level (see footnote) 0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	1.2g	1.3g	1.4g	1.5g	1.6g	1.7g	1.8g	1.9g
Climb	1,500-3,500	120	2								4	1						
		130	10				1	3	19	41	51	16	2	1				
		140	16		1	1	2	3	7	52	100	22	8	1				
		150	20				2	3	13	64	99	13	3	1	1			
		160	9						9	37	60	22	4	2				
		170	1								6							
			58		1	1	5	9	48	194	320	74	17	5	1			
	3,500-5,500	120	1							2	7	1						
		130	10						3	8	16	1						
		140	30		1	1	3	4	11	47	71	10	4	1				
		150	47				1	2	19	75	125	21	4					
		160	22				1	1	2	37	64	11	1					
		170	3						5	5	6	2	1					
			113		1	1	5	7	40	174	289	46	10	1				
	5,500-7,500	130	6					2	7	14	16	9	2	1	1			
		140	23						2	12	29	12	2	1	1	1		
		150	40						3	24	44	9	1					
		160	10						1	14	12							
		170	1							0	0							
			80					2	13	64	101	30	5	2	2	1		
	7,500-9,500	130	6						1	12	15	2	1					
		140	7						1	1	10							
		150	7							0	0							
		160	1							0	0							
			21						2	13	25	2	1					
	Climb total		272		2	2	10	18	103	445	735	152	33	8	3	1		
Cruise	0-1,500	110	1							0	0							
		120	4					2	8	33	85	20	3	1				
		130	8						8	37	44	8						
		140	12		1	1	1	6	31	81	150	47	4	2	1	1		
		150	13						17	38	77	29						
		160	19				3	10	69	180	343	116	15	6				
		170	2				1	2	11	24	57	24	2					
			59		1	1	5	20	144	393	756	244	24	9	1	1		
	1,500-3,500	110	1							0	0							
		120	6						3	15	58	19	6	3				
		130	33						1	2	7							
		140	54				1	1	10	45	114	22	3					
		150	74	1	1	1	3	15	77	285	422	107	14	4				
		160	72		1	2	9	24	78	309	408	92	20	2				
		170	17				2	4	34	110	107	38	8	5	1	1	1	1
		180	1							0	0							
			258	1	2	3	15	44	203	766	1116	278	51	14	1	1	1	1
	3,500-5,500	120	1							0	7	3						
		130	22						1	4	1							
		140	62		1	2	3	7	30	89	127	32	5	2				
		150	155				1	5	44	151	211	45	13	4				
		160	152		1	1	1	5	28	122	178	34	7	2				
		170	25						13	33	23	3						
		180	2							0	1							
			419		2	3	5	17	116	399	548	117	25	8				

TABLE II (Contd)

Flight Condition	Altitude above sea level feet	Indicated airspeed knots	Recording Time (10.5 min units)	Number of times each level of acceleration was exceeded Nominal Acceleration Level (see footnote)														
				0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	1.2g	1.3g	1.4g	1.5g	1.6g	1.7g	1.8g	1.9g
Cruise (Contd)	5,500-7,500	130	16				1	3	7	22	26	6	2	1				
		140	158			1	3	11	37	93	101	32	12	8	2	1		
		150	465		1	2	4	18	73	222	270	60	12	6	2	1		
		160	293				2	8	32	64	118	22	8	3				
		170	24						6	13	28	5						
			956		1	3	10	40	155	414	543	125	34	18	4	2		
	7,500-9,500	120	2							0	3	1						
		130	37					1	5	41	55	5	1					
		140	231				3	6	30	147	243	36	7	1				
		150	506		1	3	7	14	40	134	167	37	7	1				
		160	112					2	21	62	59	9	2					
		170	11						1	4	12	5						
			899		1	3	10	23	97	388	539	93	17	2				
	9,500-11,500	120	1							0	0							
		130	18					1	6	17	24	8						
		140	70				1	3	20	72	95	17	2	1				
		150	121						8	42	55	16	5	2				
		160	15				1	2	5	14	11	4						
		170	1							0	0							
			226				2	6	39	145	185	45	7	3				
	Cruise total		2817	1	7	13	47	150	754	2505	3687	902	158	54	6	4	1	1
Descent	0-1,500	100	1							3	9	4						
		110	1							3	18	2						
		120	7						1	11	19	3						
		130	2					1	2	22	43	12						
		140	5						25	49	57	20	5					
		160	1				1	1	8	16	14	6						
		170	2							0	0							
			19				1	2	36	104	160	47	5					
	1,500-3,500	100	2							3	11	10	5	2	1			
		110	2							5	21	1						
		120	22				1	1	9	51	141	25	1					
		130	28					3	21	83	159	38	7	3				
		140	33				1	8	27	96	157	39	5	2	1			
		150	27					1	17	66	151	27	6	1	1			
		160	18				1	3	9	44	70	12	4	1	1			
		170	6				1	4	40	78	84	27	7	2				
			138				4	20	123	426	794	179	35	11	4			
	3,500-5,500	110	2							1	3							
		120	3							3	11	5	2	1				
		130	12						2	15	45	6	1					
		140	31		1	2	3	6	36	104	147	50	10	6	1			
		150	39				1	5	27	77	143	24	5	2				
		160	35		1	2	8	14	46	133	180	55	9	6				
		170	34						6	41	67	18	1	1	1	1		
		180	4				1	1	1	2	2							
			160		2	4	13	26	118	376	598	158	28	16	2	1		

TABLE II (Contd)

Flight Condition	Altitude above sea level feet	Indicated airspeed knots	Recording Time (10.5 min units)	Number of times each level of acceleration was exceeded Nominal Acceleration Level (see footnote)														
				0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	1.2g	1.3g	1.4g	1.5g	1.6g	1.7g	1.8g	1.9g
Descent (Contd)	5,500-7,500	120	2							0	0							
		130	5							0	9							
		140	12					1	7	25	38	9	2					
		150	39					3	18	56	64	16	1	1				
		160	35				1	1	9	35	35	4	1					
		170	17							13	21	3						
		180	3				1	4	13	27	28	11	3	2	1			
			113				2	9	47	156	195	43	7	3	1			
	7,500-9,500	120	1						2	10	21	4						
		130	1							0	0							
		140	7							5	5	1						
		150	10							0	1	1						
		160	13							1	10							
		170	2						1	4	3	1						
			34						3	20	40	7						
	Descent total		464		2	4	20	57	327	1082	1787	434	75	30	7	1		

The necessary corrections for instrument error to the nominal acceleration levels are:

1.2g, 1.3g, 1.4g	+0.03g
1.5g and greater	+0.02g
0.8g, 0.7g, 0.6g	-0.03g
0.5g and smaller	-0.02g

TABLE III

Summary of Gust Speeds Encountered

Flight Condition	Altitude above sea level I.C.A.N.	Mean Altitude in band	Flying distance recorded	Estimated number of times a gust speed was exceeded in the recorded distance flown									
				Vertical gust speed ft/sec E.A.S. (+ up, − down)									
	feet	feet	Statute miles	-30	-25	-20	-15	-10	10	15	20	25	30
Climb	1500-3500		1750		1	5	19	107	172	27	4		
	3500-5500		3600		1	3	11	81	122	12	1		
	5500-7500		2620				6	28	59	11	2	1	
	7500-9500		680					7	12	2			
Descent	0-1500		506				5	82	126	26	2		
	1500-3500		3890			2	32	260	470	66	14	3	1
	3500-5500		5260		1	4	29	178	270	34	10		
	5500-7500		3880				6	62	68	7			
	7500-9500		1180					11	23	3			
Climb & Descent	0-1500	600	506				5	82	126	26	2		
	1500-3500	2400	5640		1	7	51	367	642	93	18	3	1
	3500-5500	4500	8860		2	7	40	259	392	46	11		
	5500-7500	6400	6500				12	90	127	18	2	1	
	7500-9500	8400	1960					18	35	5			
Cruise	0-1500	900	1740		1	2	37	250	450	57	5	1	
	1500-3500	2500	8020	1	2	5	45	360	520	55	9	2	1
	3500-5500	4700	13700		1	4	22	198	235	29	6		
	5500-7500	6500	32300		1	5	43	256	220	38	12	2	
	7500-9500	8500	30500		1	9	27	192	188	21	2		
	9500-11500	10100	7790			1	8	72	88	9	2		

TABLE IV

Relative turbulence each month recorded during climb and descent (1,500-5,500 feet)

Month	No. of recording intervals	No. of intervals with gust > 10 ft/sec	Recording Distance in Statute miles	No. of gusts exceeding 10 ft/sec (up + down)	Miles per gust	Turbulence Ratio $\frac{\text{Yearly miles/gust}}{\text{Monthly miles/gust}}$
1	14	4	437	66	6.57	1.2
2	33	13	1023	208	4.92	1.7
3	28	13	867	81	10.7	0.76
4	54	33	1678	240	7.00	1.2
5	79	41	2450	402	6.10	1.3
6	19	9	603	121	4.98	1.7
7	75	34	2322	236	9.84	0.82
8	30	11	931	97	9.60	0.85
9	33	22	1023	188	5.44	1.5
10	38	9	1180	32	36.9	0.22
11	36	11	1117	73	15.3	0.53
12	29	6	899	31	29.0	0.28
Totals	468	206	14,530	1775	Average 8.13	

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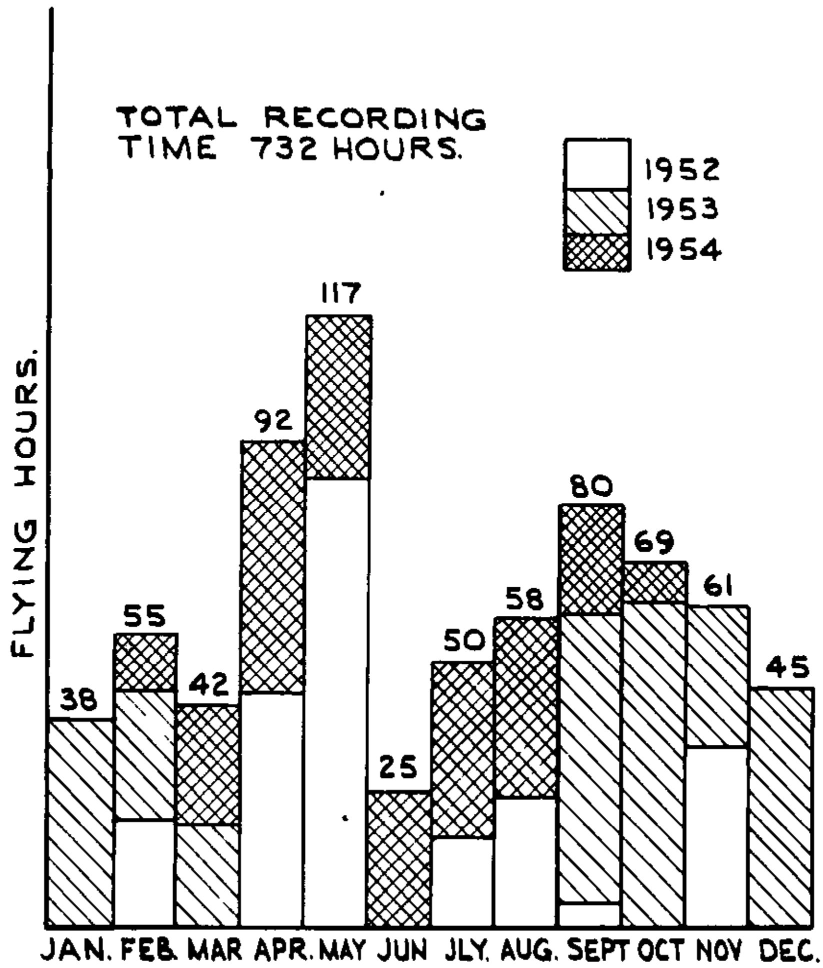
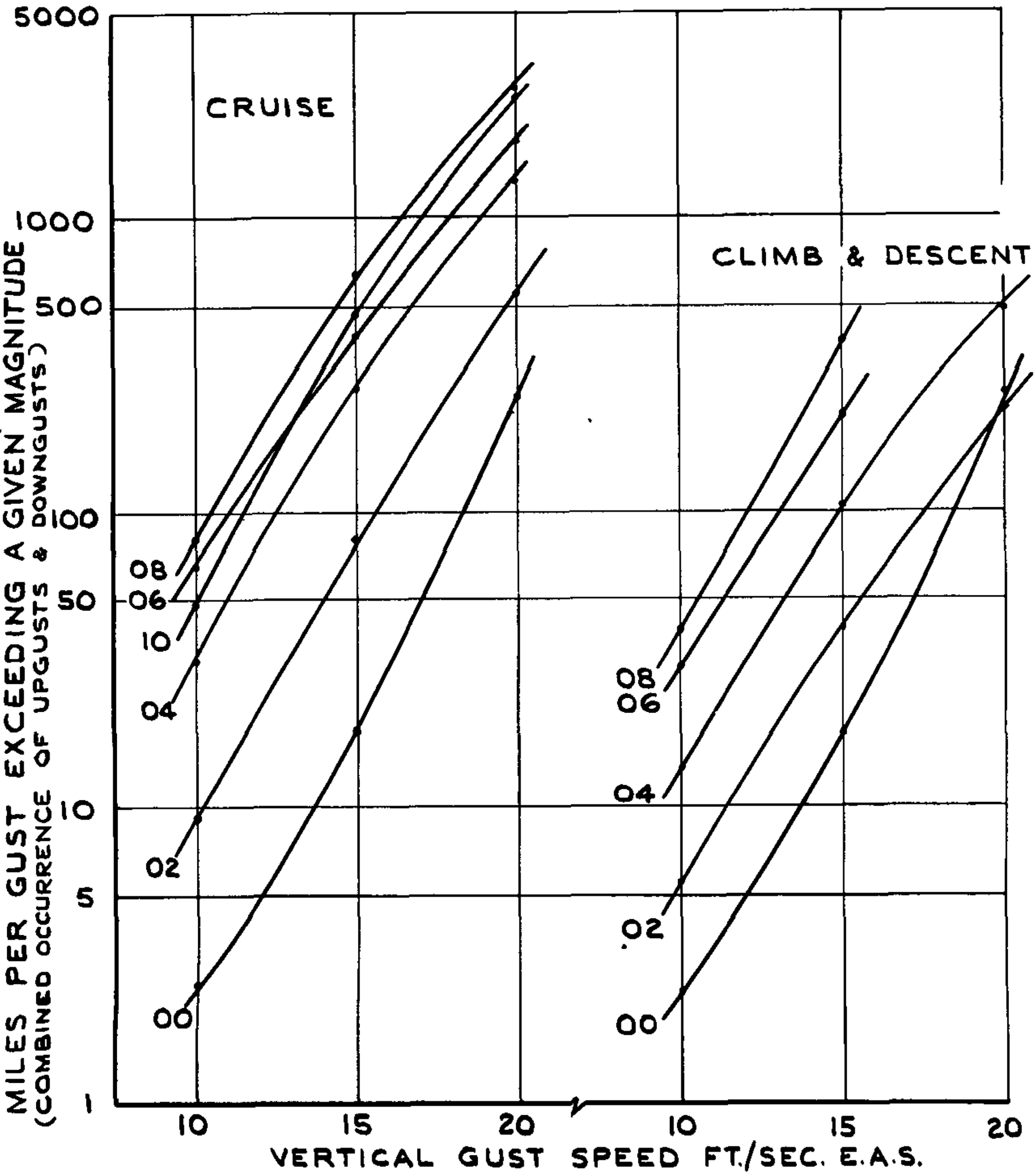


FIG I. MONTHLY DISTRIBUTION OF RECORDED FLYING TIME



ALTITUDE BAND	ALTITUDE RANGE FEET	MEAN ALTITUDE FEET		DISTANCE. ST. MILES	
		CRUISE	CL'& D	CRUISE	CL'& D.
00	0-1500	900	600	1740	506
02	1500-3500	2500	2400	8020	5640
04	3500-5500	4700	4500	13700	8860
06	5500-7500	6500	6400	32300	6500
08	7500-9500	8500	8400	30500	1960
10	9500-11500	10100	—	7790	—

FIG 2. GUST SPECTRA AT DIFFERENT ALTITUDES.

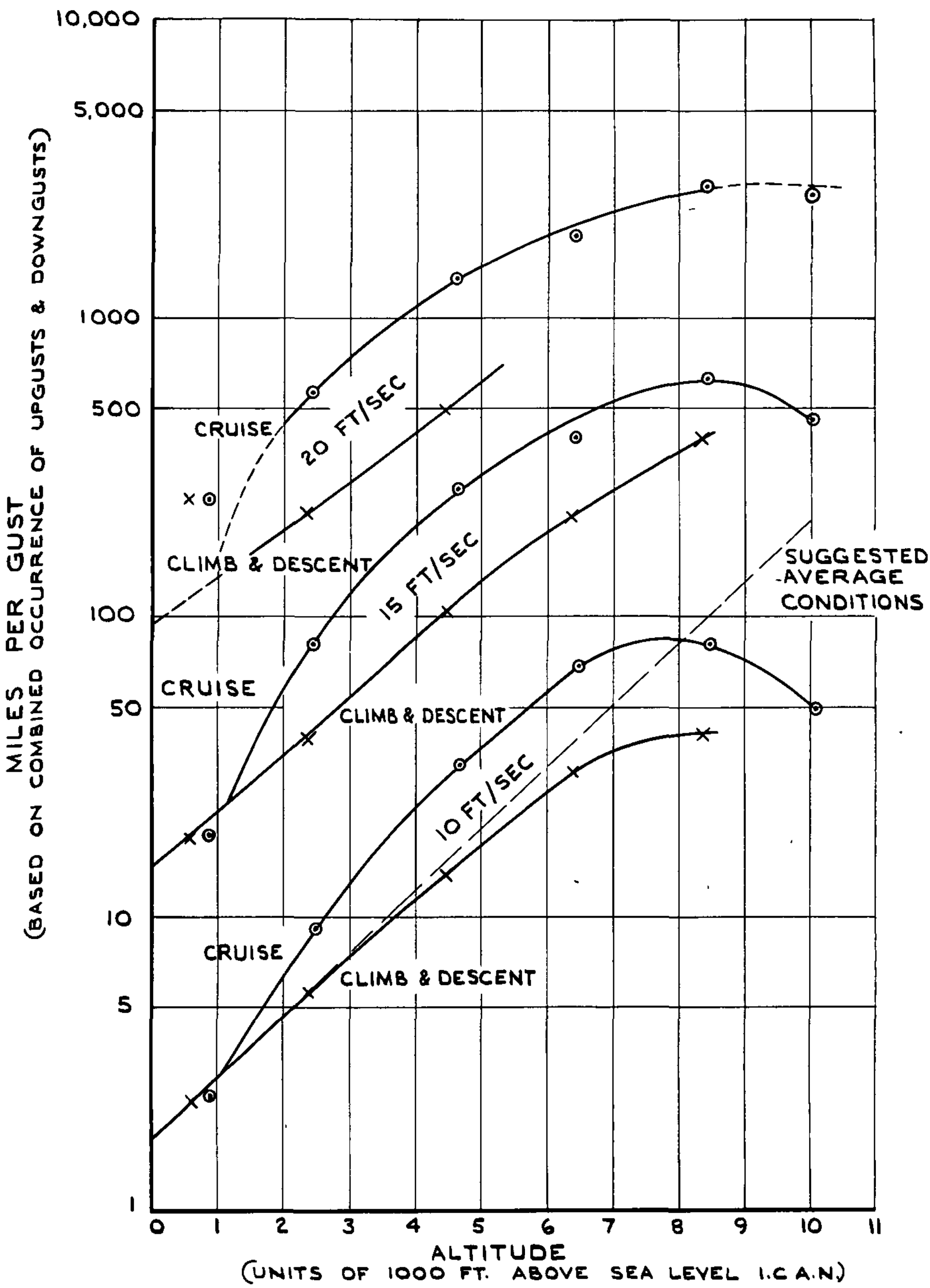


FIG 3. VARIATION OF TURBULENCE WITH ALTITUDE IN TERMS OF GUSTS EXCEEDING 10 FT/SEC 15 FT/SEC AND 20 FT/SEC.

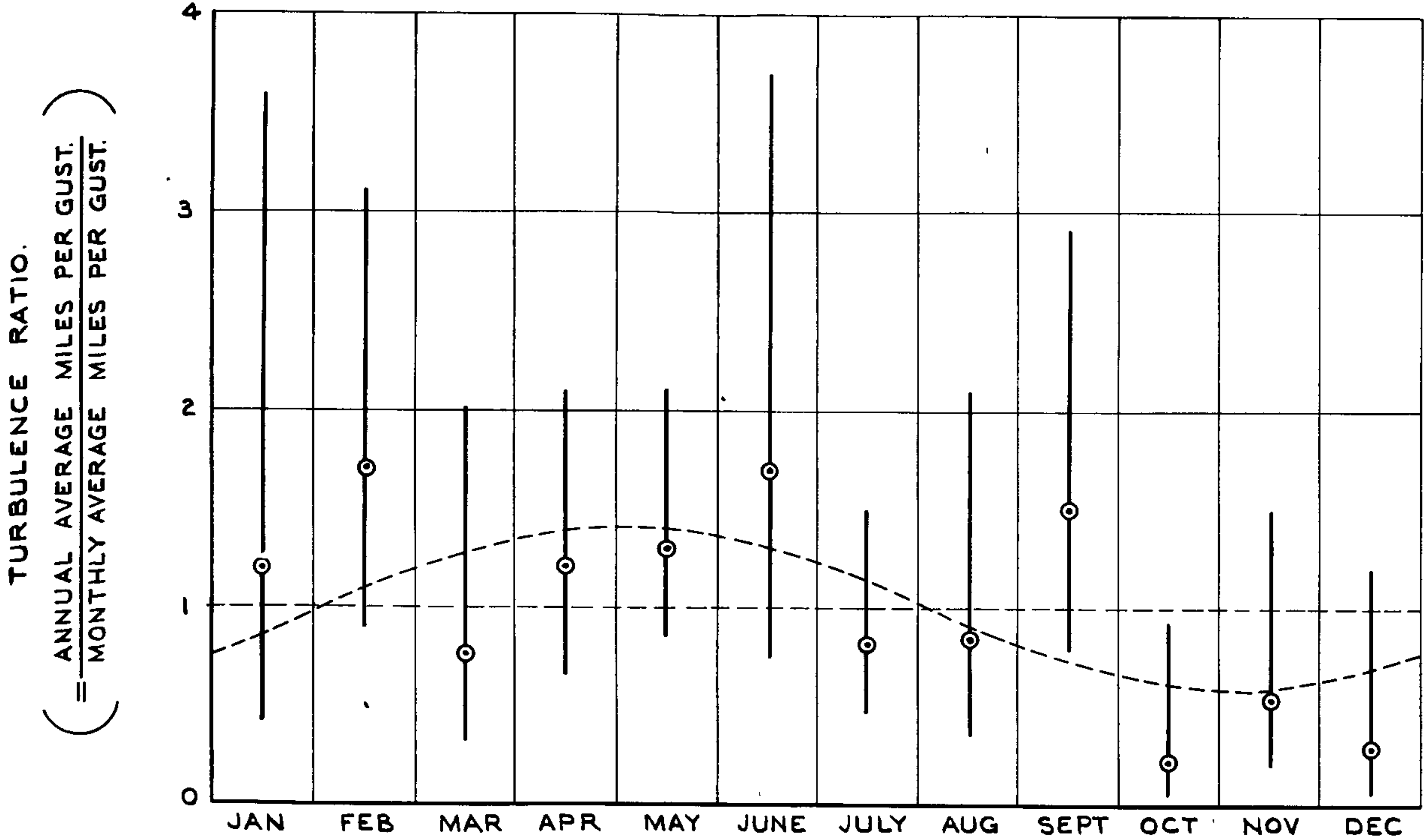


FIG 4. MONTHLY AVERAGE RECORDED TURBULENCE IN TERMS OF 10 FT/SEC GUST FREQUENCY.

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