4.15. ESTIMATING THE PHYSICAL DIMENSIONS OF BIRDS BY RADAR.

MR. T. BROUGH AND MR. E.W. HOUGHTON, U.K.

Paper for 9th Bird Strike Committee Europe Conference, Frankfurt, June, 1974 - Estimating the Physical Dimensions of Birds by Radar

Edward Houghton* and Trevor Brough**

1. INTRODUCTION

Although military and ATC (Air Traffic Control) surveillance radars can be used to observe the movements of birds at night and in bad weather conditions, when the range of optical and infra-red sensors is severely limited, they have at least one important limitation. This shortcoming is that it is generally impossible to identify a target directly on the PPI (Plan Position Indicator) with a high probability of success unless the target transmits a code message such as by IFF (identification, friend or foe).

The PPI operator has no difficulty in discriminating between the fast movements of the aircraft echoes and the slow movements of bird echoes, and experienced operators can usually distinguish between bird echoes and slow moving echoes of meteorological origin. As a result of careful and lengthy correlation studies between visual and radar observations, some birds movements generating extended PPI echo patterns have been related to particular species, such as starlings (_Sturnus vulgaris_) and honey buzzards, (_Pernis apivorus_), but the species producing unmistakable echo patterns are relatively few.

Since the origins of radar, engineers have from time to time been preoccupied with ways of identifying unco-operative targets such as birds. This search for identifying features has been called looking for target "signature".

By using a high resolution radar it is possible to follow one or two birds alone for sufficient time to obtain an echo signal record from which a "signature" can be extracted. (For simplicity we shall assume the "signature" is contained only in the echo waveform, and neglect the identification data obtainable from correlating echo and flight characteristics.)

Two properties of the flying animal target, the periodic variation of echo intensity and the doppler rate, permit a fairly quick and direct way of relating identifiable physical properties of the target with parameters obtained by radar. Bird activity modulation (BAM) fully describes the fluctuating echo intensity "signature" obtained from a bird and takes into account fluctuations of echoing area due to head and body movements as well as rhythmical wing-flapping.

Some examples of BAM waveforms are given in fig.1 and fig. 2 where the vertical axis is radar echo amplitude and the horizontal axis is time in seconds. Note that the time scales have been made different in order to show off these improved BAM waveforms to full advantage. The BAM waveform shown at thetop of fig.1 was obtained from a domestic pigeon (_Columba livia_ var.) released near to a high-resolution C-band (5cm wavelength) radar. This waveform of continuous periodic modulation can be related directly to the rhythmical wing-flapping of the bird. The BAM waveform of a visually identified kestrel (_Falco tinnunculus_)is shown at the top of fig. 2. The complex periodic waveform generated by wing-flapping is from a portion of the tape recording made while the falcon was hovering.

The complex periodic waves which make up the modulated portion of the BAM waveform can be frequency analysed to produce the spectra shown at the bottom of fig. 1 and fig. 2. The horizontal axes in these diagrams are scaled in frequency,

---

*Ministry of Defence, Royal Radar Establishment, Malvern, Worcestershire.
**Ministry of Agriculture, Fisheries and Food, Pest Infestation Control Laboratory, Tangley Place, Worplesdon, Guildford, Surrey, GU3 3LQ

and the SI unit of hertz (Hz) is used instead of the hitherto common unit of cycles per second. The chief frequency components obtained in the examples are of single spectral responses corresponding to the physical wing beat frequencies which, for the pigeon and kestrel, are centred on 5.3 Hz and 6.7 Hz respectively. Although the BAM waveforms are of periodic waves they are complex and rich in harmonics. In both examples there is a strong second harmonic of the fundamental frequency.

Although even an inexperienced worker would have no difficulty in separating out the two species from the "signature" results, a much more detailed classification would be necessary if a large number of species had to be differentiated. Furthermore, it would become more and more necessary to consider intraspecific variations, and the effect of flight variations.

However from the bird strike point of view a broad assessment may be acceptable in many situations. For example, it could be a valuable aid to air safety if species entering controlled airspace could be detected at night and in bad weather, and gauged as large birds or small ones, or heavy birds or light ones. It would be convenient if this weight or size value of a bird could be obtained from a fairly easily extracted radar parameter such as the wing beat frequency.

Radar studies on migrating birds have revealed that each species tends to have a fairly constant wing beat rate. Generally small light birds flap their wings fast and large heavy birds flap their wings slowly, and it is possible to obtain empirical relationships between wing length, weight and wing beat frequency which hold for a large number of species.

Over a limited range of species it is possible to evaluate wing beat frequency/wing length/weight relationships, which (together with a simple logic utilizing regional geography, known bird populations and seasons) can be used for sorting out potentially hazardous birds from less dangerous ones. An attempt to evaluate such relationships for a number of European birds has already been made in a previous paper (1) using available data, and these relationships have been used in estimating the potential bird strike risk at Gibraltar (2).

The remainder of this paper will be devoted to demonstrating how the wing beat frequency extracted from the "signature" can be related to physical dimensions of a bird and to revising the previous paper (1).

2. WINGBEAT FREQUENCY AND BIRD DIMENSIONAL RELATIONSHIPS

We must apologise to the expert reader who is familiar with Crawford H Greenewalt's paper on dimensional relationships for flying animals (3) for going over old ground, but without a preliminary introduction the non-expert reader is likely to get lost.

Greenewalt puts forward evidence for describing the wing flapping mechanism of flying animals by the same well known model used for mechanical oscillators (such as the pendulum). The model theory yields an equation for oscillator resonance frequency or the wing beat frequency. The wing-flapping rate is shown to be directly proportional to wing muscle weight and inversely proportional to the sum of the moments of inertia of wings, wing muscles and associated vibrating skeleton (the transverse section through the breast of a pigeon is shown in fig. 3). The theory presumes a resonance frequency for flapping wings which is to be maintained regardless of changes in wing loading, and it follows that the flapping rate will be constant for birds of similar dimensional proportions. It is shown that when the values of wing beat frequency (F) and wing length (L) for a wide range of species of similar proportions (large pectoral muscle/small pectoral muscle weight ratio) are plotted, the law of the curve is of the form FL = a constant. Further relationships between wing length, body weight and wing area are developed in the text of Greenewalt's paper. He found that different laws were required for the passerines (with large pectoral muscle/small pectoral muscle ratios of the order 10:1) utilizing a mainly down-stroke wing-flapping and the humming birds (large pectoral muscle/small pectoral muscle ration of 2:1), which use both upstroke and downstroke wing-flapping.

RRE using wing beat frequency data from [illegible] European birds [obtained by Griffiths (Loughborough University) (4) and RRE-RAE using calibrated cine-cameras], and wing lengths (obtained from Coward's British Birds) (5) and weights (obtained from a number of sources) derived empirical relationships between wing beat frequency, wing length and weight and these were given in a BSCE paper (1). This paper has since been reviewed and new values are given in the text to replace the original ones.

The first area of controversy in the previous paper was the values assigned to the wing beat frequency of each species. Bruderer et al (6) draws attention to results indicating differences in the absolute values assigned to species, which may be due to variations within species, or to nature of flight (migratory, local, diurnal or nocturnal) or to measuring errors.

The best way of obtaining data for the determination of the mean wing beat frequency and standard deviation is to use a radar and record the bird activity modulation echo on magnetic tape. Because a catalogue of visually identified radar BAM waveforms is not yet available for correlation identification purposes it is necessary to identify visually birds tracked by radar. Bruderer et al and RRE have made and evaluated such measurements but so far their results have been confined to relatively few species. RRE experience of birds measured on migration indicates that individuals flap their wings at a remarkably constant rate, and the variation about the mean can be within a few per cent. RRE has compared cine-camera records obtained from a mallard (Anas platyrhynchos) drake and duck in straight cruising flight, which shows the lighter duck was beating her wings a few per cent faster than the drake. RRE cine-records revealed that a mallard drake wing beat frequency changed from approximately 7 Hz in level flight to about 4 Hz when approaching a pool steeply through a wood, and this change corresponds to pronounced changes in wing shape.

Wing beat frequency data for use in en route bird strike prevention should embrace all values about the mean for birds in level flight. This paper does not consider birds landing and taking off or dropped from aircraft when drastic changes in wing beat frequency may occur. Until a wider range of data becomes available records taken over a number of flight situations using calibrated measuring methods such as those by Griffiths provide a good basis for initial assessment purposes. In the future this data will no doubt be revalued and the effects of the nature of flight be considered.

The second area of controversy in the previous paper concerned the values assigned to wing lengths. In ornithology, actual wing length is not recorded because it is practically impossible to determine exactly where the wing commences on the body and the length also varies with the amount of stretch. The "wing length" of ornithological text books is invariably the measurement from the wrist to the end of the longest feather which can be determined relatively accurately and it is shorter than the true wing length (fig. 4). Occasionally data for wing span is available, subject also to inaccuracies through stretch. True wing length might be determined as $\frac{1}{2}$ (wing span minus body width) but body width, like true wing length, cannot be determined with any consistency. Nevertheless, it is arguable that a better estimate of true wing length than the standard measurement from wrist to wing tip might be obtained from one half the wing span as used by Greenewalt and these are compared below. Sufficient wing span values by Magnan (7) and Geroudet (8) have been gathered together for a comparison with Coward's wrist to tip values which were used in most of the experimental calculations and the comparison is made in the text later. The wrist to wing tip data tabulated in the present paper have been obtained from the Handbook of British Birds (9).

The weights assigned to species have been revised by Pest Infestation Control Laboratory (PICL) where necessary.

These considerations and modified values have been taken into account in drawing up Table 1, which shows wing beat frequencies, wing dimensions and weights for 58 European birds. Forty-one wing beat frequency values taken by means of calibrated cine-camera by Griffiths (4) provide the bulk of the data. Additionally by the same means there are eighteen RRE-RAE measurements, eight of which substantiate Griffiths' findings. Three radar results are drawn from Bruderer <u>et al</u> (6) and five radar results where species were identified visually are from RRE, one determination confirming a finding by Bruderer <u>et al</u>. Nearly all values are based on more than 5 observations/species, and radar observation records have been generally more than two minutes long. Species with wing beat frequencies higher than 22 Hz have been omitted as being relatively unimportant as bird hazards in Europe.

Using a programme to compute the least-square fit and correlation coefficient of n pairs of data points a number of mathematical functions were examined using data from table 1, and a power curve of the form:-

$$\ln y = \ln a \pm b \ln x \qquad \ldots\ldots (1)$$

was found to give the best fit.

In deciding whether wing span lengths were to be preferred to wrist-to-tip wing lengths two programmes were run using appropriate data from Table 1. Forty paired wing beat frequency and wing span values were used to obtain the natural logarithm of wing beat frequency:

$$\ln F = \ln 1310 - 0.808 \ln L \qquad \ldots\ldots (2)$$

sample correlation coefficient $r = -0.936$

Similarly values of wing beat frequency and wrist to tip wing lengths from Coward were used to obtain the natural logarithm of wing beat frequency:

$$\ln F = \ln 624 - 0.844 \ln L \qquad \ldots\ldots (3)$$

sample correlation coefficient $r = -0.941$

The negative correlation coefficients occur because on average the wing beat frequency F decreases as wing length L increases. It can be seen from these empirical equations that there is no obvious advantage to preferring one of them.

Since there is no clear advantage to choosing equation 2 over equation 3 and wing spans are still not the desired $\frac{1}{2}$ (wing span minus body) wing lengths and are more difficult to measure and more poorly catalogued, it is proposed to continue using wrist to tip wing lengths.

Fifty-eight paired wing beat frequencies and wrist to tip wing lengths (from the Handbook) taken from Table 1 have been plotted on the graph of fig. 5. In order to accommodate the range of ordinates, the wing beat frequencies and wing lengths have been plotted on a logarithmic (base 10) scale. Using the least-square fit programme two regression equations were obtained as follows:-

(Estimated wing beat frequency) $\ln \hat{F} = \overset{\ln}{\scriptstyle\wedge}767.4 - 0.886 \ln L \ldots\ldots (4a)$

(Estimated wing length) $\ln \hat{L} = \ln 1494.6 - 1.035 \ln F \ldots (4b)$

sample correlation coefficient $r = -0.957$

The straight line for equation 4b is shown plotted over the experimental scatter diagram in fig. 5. Two different equations are generated because estimating y from x is not just the reverse of estimating x from y except when $r = 1$. In one case the line of regression of x on y is obtained by making the least square fit minimum for dx, while for the regression of y on x the least square fit is minimised for dy. Thus when wing beat frequency values are obtained from radar data the wing length values must be estimated by using equation 4b.

Fifty-eight paired wing beat frequencies and weights taken from Table 1 have been plotted in fig. 6, and two regression equations were computed as follows:-

(Estimated wing beat frequency) $\ln \hat{F} = \ln 32.55 - 0.280 \ln W$ ..... (5a)

(Estimated bird weight) $\ln \hat{W} = \ln 52{,}749 - 2.808 \ln F$ ..... (5b)

sample correlation coefficient $r = -0.888$

Equation 5b has been plotted over the scatter diagram of fig. 6.

Just before this paper was completed, Charles R. Vaughn (NASA) sent us his paper (10) containing information on measured wing beat rates of 37 American species. These birds were released from a helicopter and tracked by a high resolution C-band (5 cm wavelength) radar. The wing beat frequencies are "representative" fundamental frequencies of the automatic gain control (AGC) Fourier spectra (ie. they are analysed BAM waveforms). In some cases they are the average of 26 records of the same species, while in other cases they are just single records. Generally the BAM records were taken over one minute or more. Wing lengths were taken from the birds actually released. Measurements were taken from the bend of the closed wing to the tip of the longest primary. Thirty species taken from Vaughn's tables 3, 4 and 5 are given in table 2 together with their averaged wing beat frequencies and their wing lengths.

As a matter of interest these thirty paired wing beat frequencies and wing lengths have been added to the fifty-eight paired values given in Table 1 in order to investigate further Greenewalt's simple model. Using the least-square fit two regression equations were obtained from these eighty-eight paired of values as follows:-

(Estimated wing beat frequency) $\ln \hat{F} = \ln 441 - 0.791 \ln L$ ...... (6a)

(Estimated wing length) $\ln \hat{L} = \ln 1531 - 1.096 \ln F$ ...... (6b)

sample correlation coefficient = -0.931

The straight line for equation 6b together with the 95% confidence limits are shown plotted over the experimental scatter diagram in fig.7. For example, the estimated wing length and 95% confidence interval estimate for an observed wing beat frequency of 5.63 Hz are

$$\hat{L} = 231\text{mm, and interval } 142 - 376 \text{ mm}$$

Hence by obtaining the wing beat frequency from a BAM waveform the wing length can be estimated to within + 63% - 38% at the 95% confidence level.

Although the regions of the European and American species do not normally overlap, their values enable the simple formula to be favourably demonstrated.

3. UNCERTAINTIES

The empirical relationships given in the last section are used to estimate wing lengths or weights of birds from radar-measured wing beat frequencies. How well can the empirically derived equations be relied upon to predict bird dimensions given accurately observed wing beat frequencies? One way of answering this question is to check that the distribution of estimated and experimental wing length and weight residuals are without bias and randomly distributed about the regression line and then to calculate confidence levels. These conditions have been assumed here for although they are approximately true at the shorter wing lengths there is bias at the longer wing lengths. Using an expression given by Draper et al. (11), 95% confidence interval estimates for a single (future) value of wing length corresponding to a desired observed wing beat frequency have been plotted each side of the calculated line in fig. 5. For example, the estimated wing length and 95% confidence interval estimate for an observed wing beat frequency of 5 Hz are

$\hat{L}$ = 283 mm, and interval 194 - 410 mm

The 95% confidence interval estimated for a single (future) value of weight corresponding to a desired observed wing beat frequency have been plotted each side of the calculated line in fig. 6. For example, the estimated weight and 95% confidence interval estimate for an observed wing beat frequency of 10 Hz are

$\hat{W}$ = 82 g, and interval 15 - 462 g

Hence by obtaining the wing beat frequency from the BAM waveform and using the above procedure we can estimate the wing length and weight in the examples to within + 45% - 31% and + 463% - 82% at the 95% confidence level, respectively.

4. DISCUSSION AND CONCLUSIONS

This study using a sample population of 58 European birds confirms Greenewalt's conclusions that empirical relationships can be found between wing beat frequency and physical dimension. It is important to bear in mind, when considering the magnitude of the dimensional uncertainties, that there is no alternative simpler method of estimating the dimensions of birds at relatively long range at night and in bad weather than by radar. En passant it may come as a surprise to the layman to know that radar designers would go wild with excitement if they could achieve the same accuracy in estimating the size of a glider or light aircraft. The uncertainties in estimates of total weight are, as one might expect from the simple model, much poorer than those obtained for wing length. In either case uncertainties of wing length or weight are to a first order unaffected by distance from radar if a bird can be separated from unwanted targets and lies within detection range. Good BAM records can be obtained on single birds from 1 to 10 nautical miles with mobile tracking radars and at ranges of greater than 20 nautical miles with fixed radars.

Since true wing lengths, that is, ½ (wing span minus body width), are not readily available comparisons were made between empirical equations obtained by using forty wing span (from Magnan and Geroudet) and wrist to wing tip (from Coward) values. More recently, comparisons were made between equations computed by using fifty-eight wing span (from Magnan and Geroudet) and wrist to wing tip (from the Handbook) values given in this paper. No preference was indicated as a result of these comparisons, but as wrist to wing tip values are easier to measure and better catalogued it is proposed to continue using them.

The study shows that relatively simple empirical relationships can be evaluated which could be useful in estimating the dimensions of birds intruding controlled air space. The dimensions of wing length can be estimated more accurately than weight. When the relationships can be used they are unaffected by distance from radar (within the detection range of the equipment). Equations are best calculated from a sample population of as many species as possible with values distributed as uniformly as possible along the regression curve and overlapping the desired dimension scales.

Further data obtained by radar on bird wing beat frequencies are desirable in order to determine intra and interspecific variations more precisely.

5. ACKNOWLEDGEMENTS

The authors would like to thank the following for their help and advice: their colleagues of the Photographic Unit RRE; of the Instrumentation Range, RAE; and Tommy Capp, RRE Drawing Office who was responsible for the layout of sketches and diagrams. The RAE radar team of Dave Spencer, Ken Davies and Mervyn Davies obtained the RAE waveforms and the RRE analysis team of Frank Blackwell and Bill Wilmot produced the frequency spectra.

Contributed by permission of the Directors of RRE and PICL, Copyright Controller HBMSO.

6.

REFERENCES

1. Houghton, E.W. and Blackwell, F.	(1972)	"Use of Bird Activity Modulation Waveforms in Radar Identification" 7th BSCE London Conference, June (supplementary paper to main report)
2. Houghton, E.W.	(1973)	"Highlights of the Nato-Gibraltar Bird Migration Radar Study" 8th BSCE Paris Conference. May (supplementary paper to main report)
3. Greenewalt, C.H.	(1962)	"Dimensional Relationships for Flying Animals" Smithsonian Misc. Coll 144, No.2.
4. Griffiths, M.E.	(1970)	"Wingbeat Frequencies & Flight Patterns of the more common Migrant Birds of the British Isles and Europe" University of Technology, Loughborough, Report No. 9 December. (Mintech Agreement AT/2170/08/RDI).
5. Coward, T.A.	(1947)	"The Birds of the British Isles and their Eggs" 3 volumes Frederick Warne & Co Ltd., London
6. Bruderer, B., Jacquat, B., and Bruckner, U.	(1972)	"Zur Bestimmung von Flugelschlagfrequenzen tag und nachtziehender Vogelarten mit Radar" Der Ornithologische Beobachter 69, p 189-206
7. Magnan, A.	(1922)	"Les caracteristiques des oiseaux" Ann. Sc. Naturelle, Series 10, Vol. 5, p 125-334
8. Geroudet, P.	(1967)	Les Echassiers
"	(1959)	Les Palmipedes (2nd ed. revised)
"	(1961)	Les Passereaux I Du coucou aux corvidés

8. (continued)

Geroudet, P. (1963) Les Passereaux II Des mesanges aux fauvettes

" (1957) Les Passereaux III Des pouillots aux moineaux

Delachaux and Niestlé, Neuchatel (Suisse).

9. Witherby, H.F. et.al (1943) revised "The Handbook of British Birds" 5 volumes, H.F. & G. Witherby Ltd London

10. Vaughn, C.R. (1974) "Intraspecific Wingbeat Rate Variability and Species Identification using Tracking Radar" Conference on the Biological Aspects of the Bird/Aircraft Collison Problem, Clemson University, USA, February.

11. Draper, N.R., & Smith, H. (1966) "Applied Regression Analysis" Chapter 1, p 24, John Wiley Inc New York

EUROPEAN SPECIES

NO.	SPECIES	WING BEAT FREQUENCY DETERMINED BY CINE-CAMERA OR RADAR (Hz)	WING LENGTH (mm)		PICL WEIGHT W(g)
			WING SPAN	WRIST-TIP	
1	Chiff-Chaff (<u>Phylloscopus collybita</u>)	22.2	174	58	7.5
2	Willow Warbler (<u>Phylloscopus trochilus</u>)	21.2 *	185	65	8.7
3	Sedge Warbler (<u>Acrocephalus schoenobaenus</u>)	20.7	192	67	11.2
4	Goldfinch (<u>Carduelis carduelis</u>)	19.0 *	248	77	16.0
5	Garden Warbler (<u>Sylvia borin</u>)	18.2	220	77	18.0
6	Linnet (<u>Acanthis cannabina</u>)	17.8 ≠	248	79	14.0
7	Whitethroat (<u>Sylvia communis</u>)	17.2	225	73	21.6
8	Chaffinch (<u>Fringilla coelebs</u>)	17.0 ø	285	84	22.0
9	Brambling (<u>Fringilla montifringilla</u>)	16.8 *	251	89	23.0
10	Redstart (<u>Phoenicurus phoenicurus</u>)	16.7	256	77	14.5
11	Meadow Pipit (<u>Anthus pratensis</u>)	16.6	259	80	18.5
12	Greenfinch (<u>Carduelis chloris</u>)	16.1 ≠ ø	270	87	27.0
13	Wheatear (<u>Oenanthe oenanthe</u>)	13.2	240	94	25.5
14	Skylark (<u>Alauda arvensis</u>)	12.1 ⌿	317	111	40
15	Dunlin (<u>Calidris alpina</u>)	11.9	360	111	60
16	Starling (<u>Sturnus vulgaris</u>)	11.6 ⌿	391	127	85
17	Redwing (<u>Turdus iliacus</u>)	11.5 ⌿	367	116	60

TABLE 1 (continued) EUROPEAN SPECIES

No.	SPECIES	WING BEAT FREQUENCY DETERMINED BY CINE-CAMERA OR RADAR (Hz)	WING LENGTH (mm)		PICL WEIGHT W(g)
			WING SPAN	WRIST-TIP	
18	Sand Martin (*Riparia riparia*)	10.5	314	105	14
19	Blackbird (*Turdus merula*)	10.0 *	406	122	100
20	Bee-eater (*Merops apiaster*)	9.8 ≠	385	147	55
21	House Martin (*Delichon urbica*)	9.5 ø	292	110	18
22	Knot (*Calidris canutus*)	8.9	503	168	109
23	Snipe (*Gallinago gallinago*)	8.6	448	134	140
24	Mistle Thrush (*Turdus viscivorus*)	8.5	440	152	120
25	Fieldfare (*Turdus pilaris*)	8.4	429	144	100
26	Swift (*Apus apus*)	8.2 ≠	420	172	40
27	Teal (*Anas crecca*)	8.0	578	180	350
28	Wigeon (*Anas penelope*)	7.5	855	254	700
29	Golden Plover (*Pluvialis apricaria*)	7.4	585	188	200
30	Gadwall (*Anas strepera*)	7.4 *	835	260	800
31	Bar Tailed Godwit (*Limosa lapponica*)	7.2	733	214	270
32	Redshank (*Tringa totanus*)	6.9	516	157	130
33	Pintail (*Anas acuta*)	6.9	916	263	890
34	Ruff (*Philomachus pugnax*)	6.7	632	174	180
35	Mallard (*Anas platyrhynchos*)	6.6 ≠	900	264	1140

TABLE 1 (continued) EUROPEAN SPECIES

NO.	SPECIES	WING BEAT FREQUENCY DETERMINED BY CINE-CAMERA OR RADAR (Hz)	WING LENGTH (mm)		PICL WEIGHT W(g)
			WING SPAN	WRIST-TIP	
36	Shoveller (*Anas clypeata*)	6.5	798	234	610
37	Oystercatcher (*Haematopus ostralegus*)	5.9	805	261	550
38	Turtle Dove (*Streptopelia turtur*)	5.7 *	529	173	135
39	Wood pigeon (*Columba palumbus*)	5.6 ⌿	751	245	500
40	Kestrel (*Falco tinnuculus*)	5.6 ⌿	744	246	200
41	Sparrow Hawk (*Accipiter nisus*)	5.4	686	214	200
42	Shelduck (*Tadorna tadorna*)	5.3	1075	323	1200
43	Jackdaw (*Corvus monedula*)	4.9	708	236	210
44	Barnacle Goose (*Branta leucopsis*)	4.6	1080	402	1600
45	Whitefront (*Anser albifrons*)	4.5 *	1410	411	2200
46	Pink-footed Goose (*Anser brachyrhynchus*)	4.4	1525	439	2500
47	Lapwing (*Vanellus vanellus*)	4.3 *	750	226	200
48	Grey Lag Goose (*Anser anser*)	4.3	1630	448	3400
49	Black-headed Gull (*Larus ridibundus*)	4.1	971	299	300
50	Rook (*Corvus frugilegus*)	3.9 ⌿	972	309	400
51	Carrion Crow (*Corvus corone*)	3.9 ⌿	894	325	550
52	Bewick's Swan (*Cygnus bewickii*)	3.9 *	1890	513	6100

NO.	SPECIES	WING BEAT FREQUENCY DETERMINED BY CINE-CAMERA OR RADAR (Hz)	WING LENGTH (mm)		PICL WEIGHT W (g)
			WING SPAN	WRIST-TIP	
53	Mute Swan (Cygnus olor)	3.5	2260	572	10500
54	Lesser Black-backed Gull (Larus fuscus)	3.4	1330	409	850
55	Herring Gull (Larus argentatus)	3.1 ⌿	1430	419	1100
56	Egyptian Vulture (Neophron percnopterus)	3.0 *	1615	490	2100
57	Great Black-backed Gull (Larus marinus)	2.9	1726	481	1600
58	Grey Heron (Ardea cinerea)	2.6	1726	446	1620

Values of wing beat frequency are taken from Griffiths (4) unless indicated as follows:-

* RRE optical value

⌿ Griffiths confirmed optically by RRE

≠ RRE radar value

ø Bruderer et al (6)

Wing span data are from Magnam (7) or Geroudet (8)

Wrist-tip data are from the Handbook of British Birds (9)

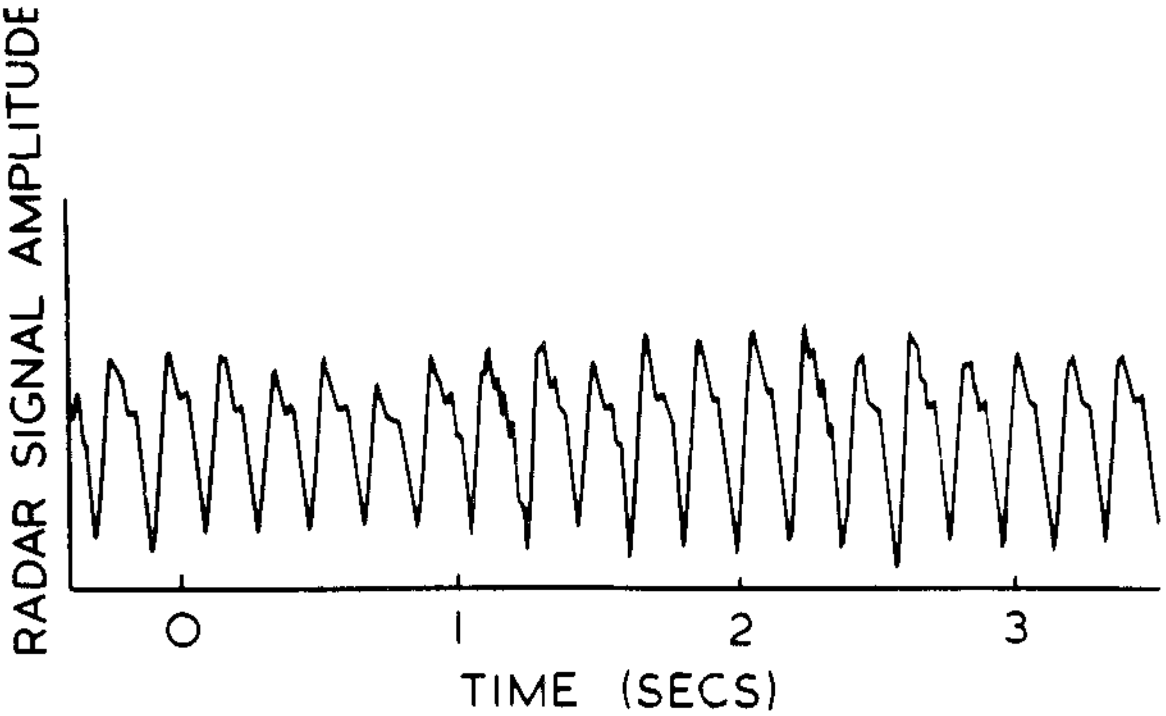
Weights are averages from a wide variety of sources

TABLE 2 WING BEAT FREQUENCIES AND BIRD DIMENSIONS

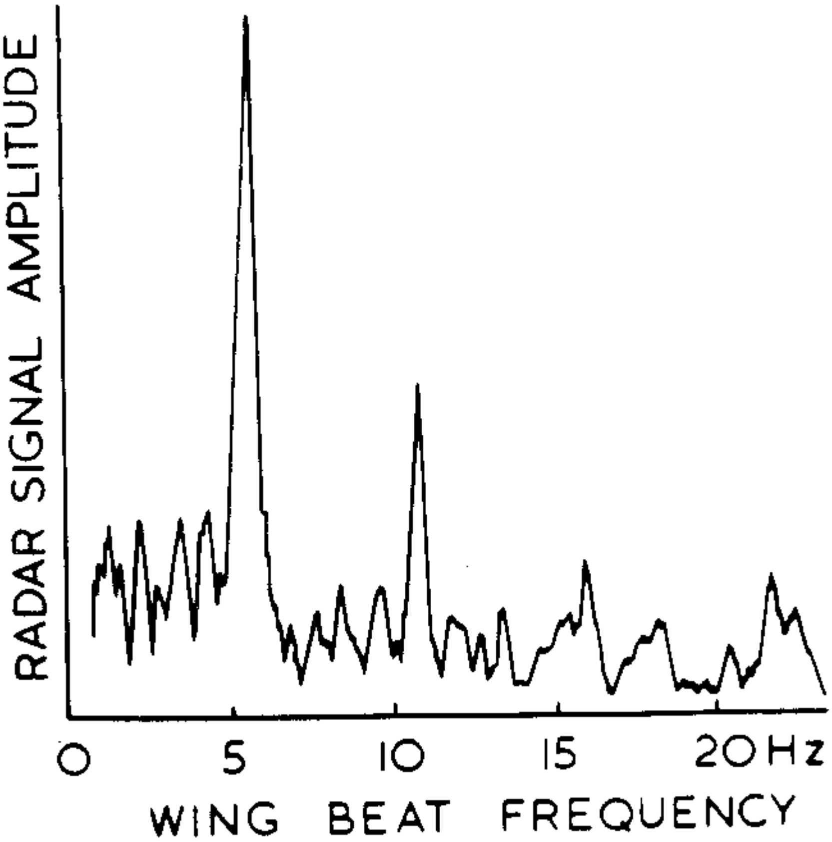
AMERICAN SPECIES

NO.	SPECIES	WING BEAT FREQUENCY (Hz)	WINGLENGTH (mm)
1	House Sparrow (*Passer domesticus*)	18.5	73
2	Yellow-throat (*Geothlypis trichas*)	17.6	53
3	Purple Finch (*Carpodacus purpureus*)	17.5	81
4	Field Sparrow (*Spizella pusilla*)	17.2	59
5	Black and White Warbler (*Mniotilta varia*)	16.8	69
6	Savannah Sparrow (*Passerculus sandwichensis*)	16.6	66
7	House Wren (*Troglodytes aedon*)	16.2	51
8	Carolina Wren (*Thryothorus ludovicianus*)	15.6	59
9	Dark-eyed Junco (*Junco hyemalis*)	15.3	77
10	Indigo Bunting (Passerina cyanea)	15.2	64
11	Yellow Warbler (*Dendroica petechia*)	14.8	61
12	Ovenbird (*Seiurus aurocapillus*)	14.7	71
13	Song Sparrow (*Melospiza melodia*)	14.6	63
14	White-throated Sparrow (*Zonotrichia albicollis*)	14.5	72
15	Yellow-rumped Warbler (*Dendroica coronata*)	14.4	69
16	Evening Grosbeak (*Hesperiphona vespertina*)	13.6	111
17	Rufous-sided Towhee (*Pipilo erythrophthalmus*)	12.4	80
18	Rose-breasted Grosbeak (*Pheucticus ludovicianus*)	11.2	96
19	Gray Catbird (*Dumetella carolinensis*)	10.3	88
20	Cardinal (*Richmondena cardinalis*)	10.2	85
21	Eastern Meadowlark (*Sturnella magna*)	9.8	118
22	Brown-headed Cowbird (Molothrus ater)	9.4	105
23	Eastern Kingbird (*Tyrannus tyrannus*)	8.6	118
24	Spotted Sandpiper (Actitis macularia)	8.4	102
25	Least Sandpiper (*Calidris minutilla*)	7.9	90
26	Common Grackle (*Quiscalus quiscula*)	7.8	122
27	Semipalmated Sandpiper (*Ereuntes pusillus*)	7.4	95
28	Blue Jay (*Cyanocitta cristata*)	6.6	131
29	Semipalmated Plover (*Charadrius semipalmatus*)	6.2	119
30	Willet (*Catoptrophorus semipalmatus*)	5.6	182

Taken from Vaughn's paper (10)
Tables 3, 4 and 5

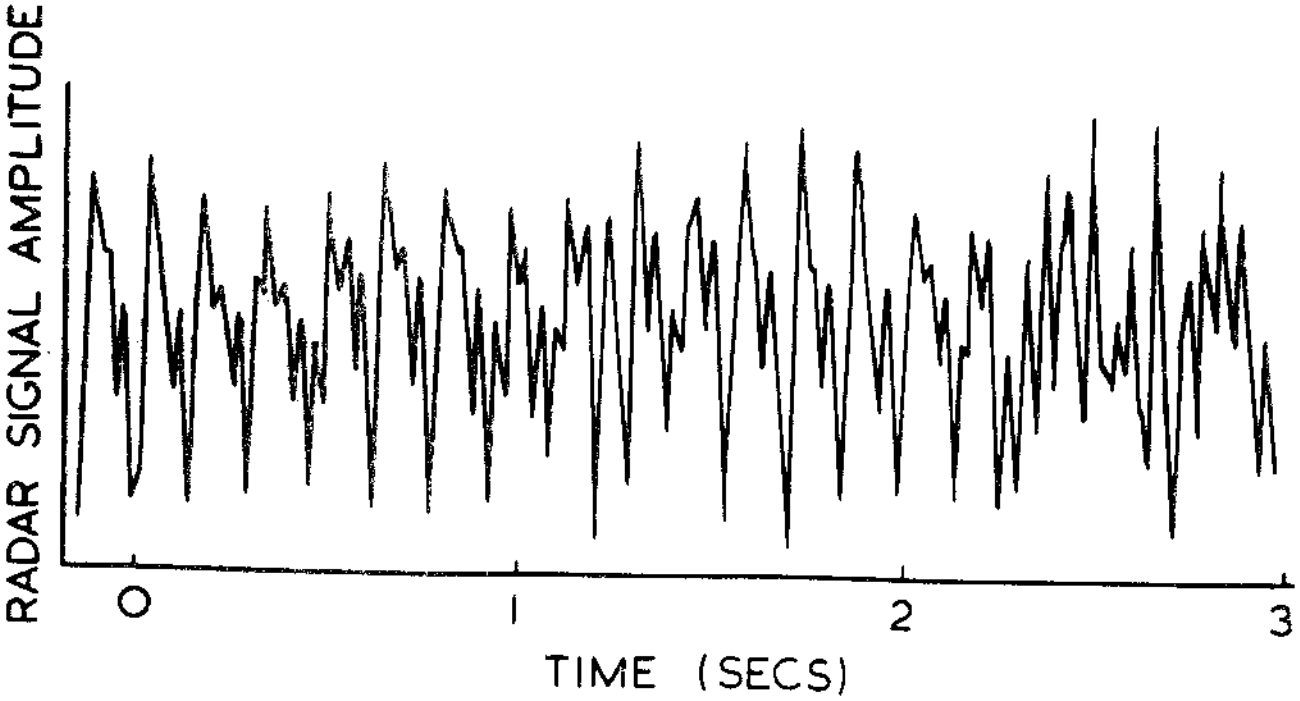


B.A.M. WAVEFORM

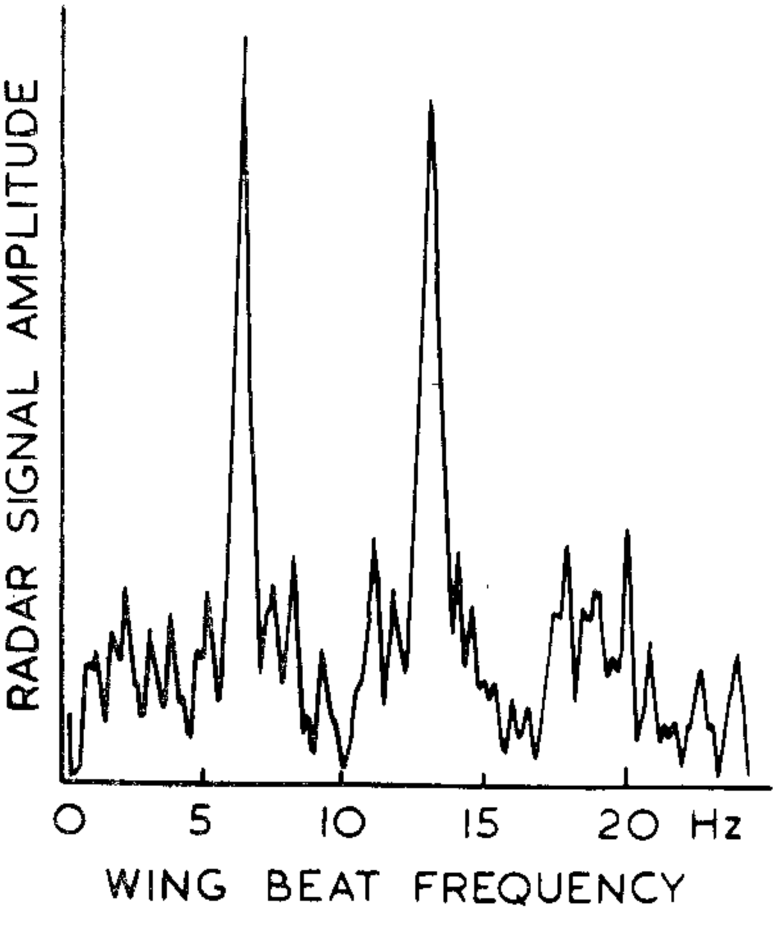


B.A.M. SPECTRUM

FIG. 1



B.A.M. WAVEFORM



B.A.M. SPECTRUM

FIG. 2

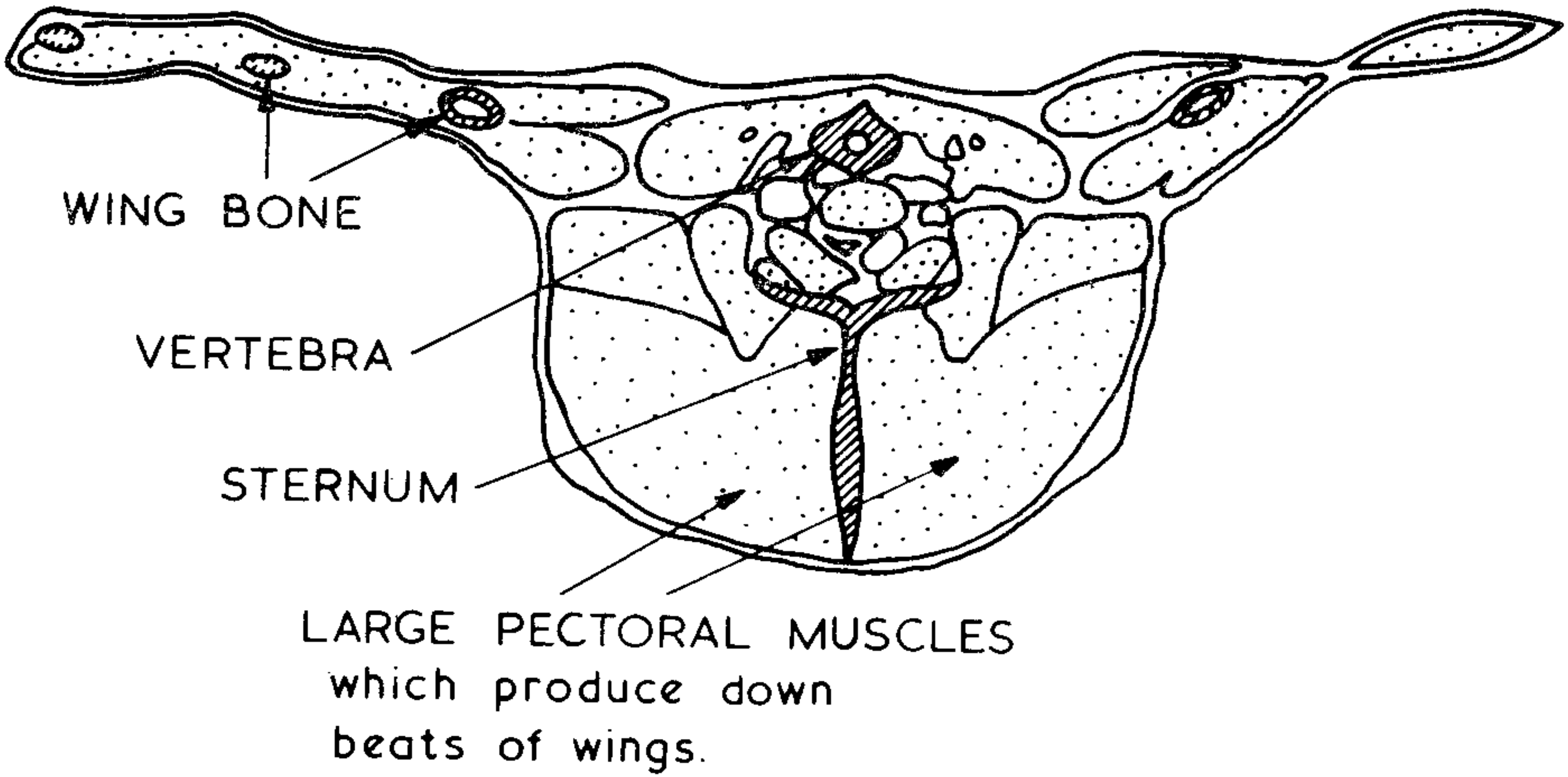


FIG. 3

TRANSVERSE SECTION THROUGH BREAST OF PIGEON

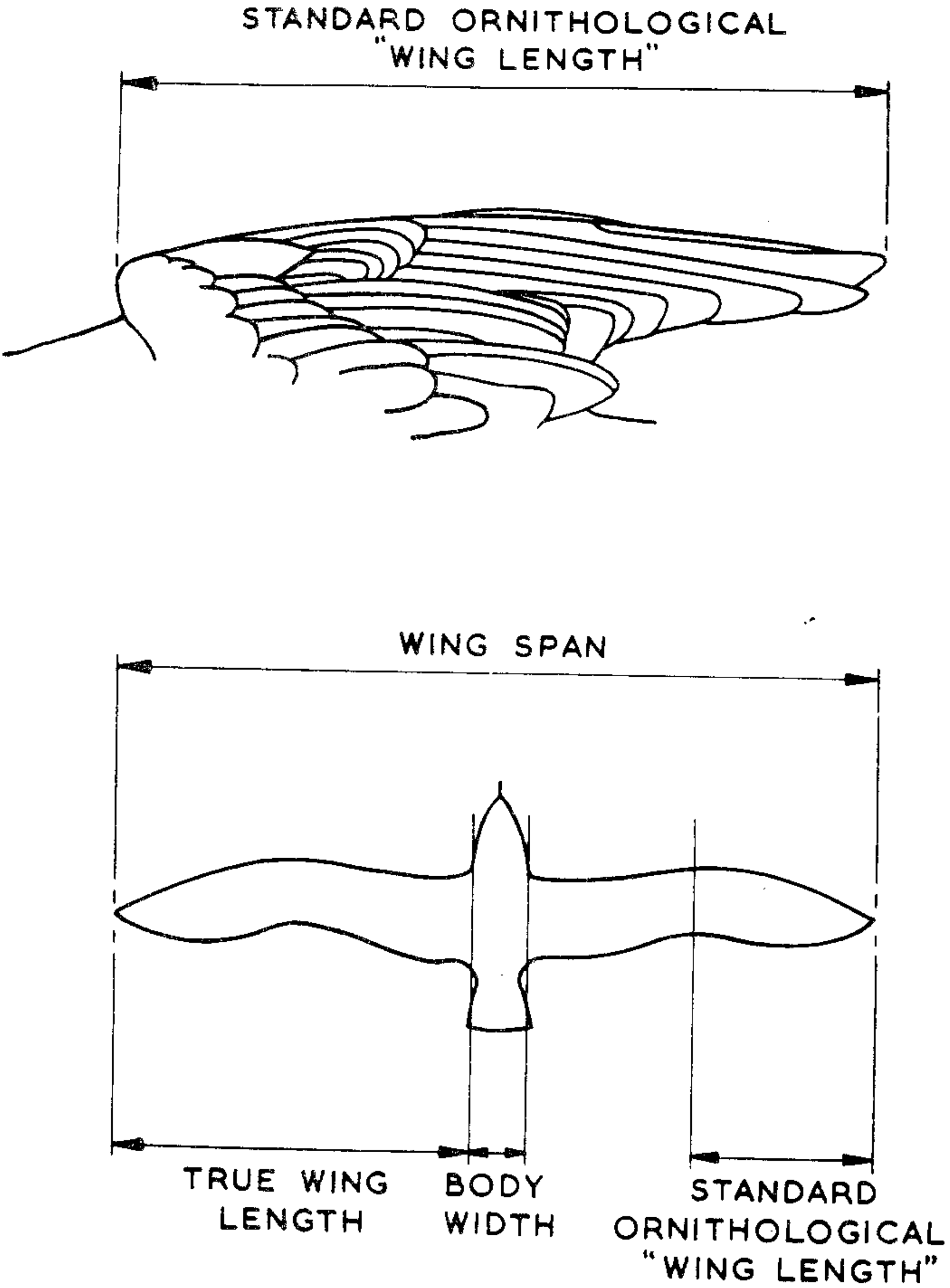


FIG. 4

THE RELATIONSHIP OF WING DIMENSIONS

FIG. 5 WINGBEAT FREQUENCY–WINGLENGTH DIAGRAM

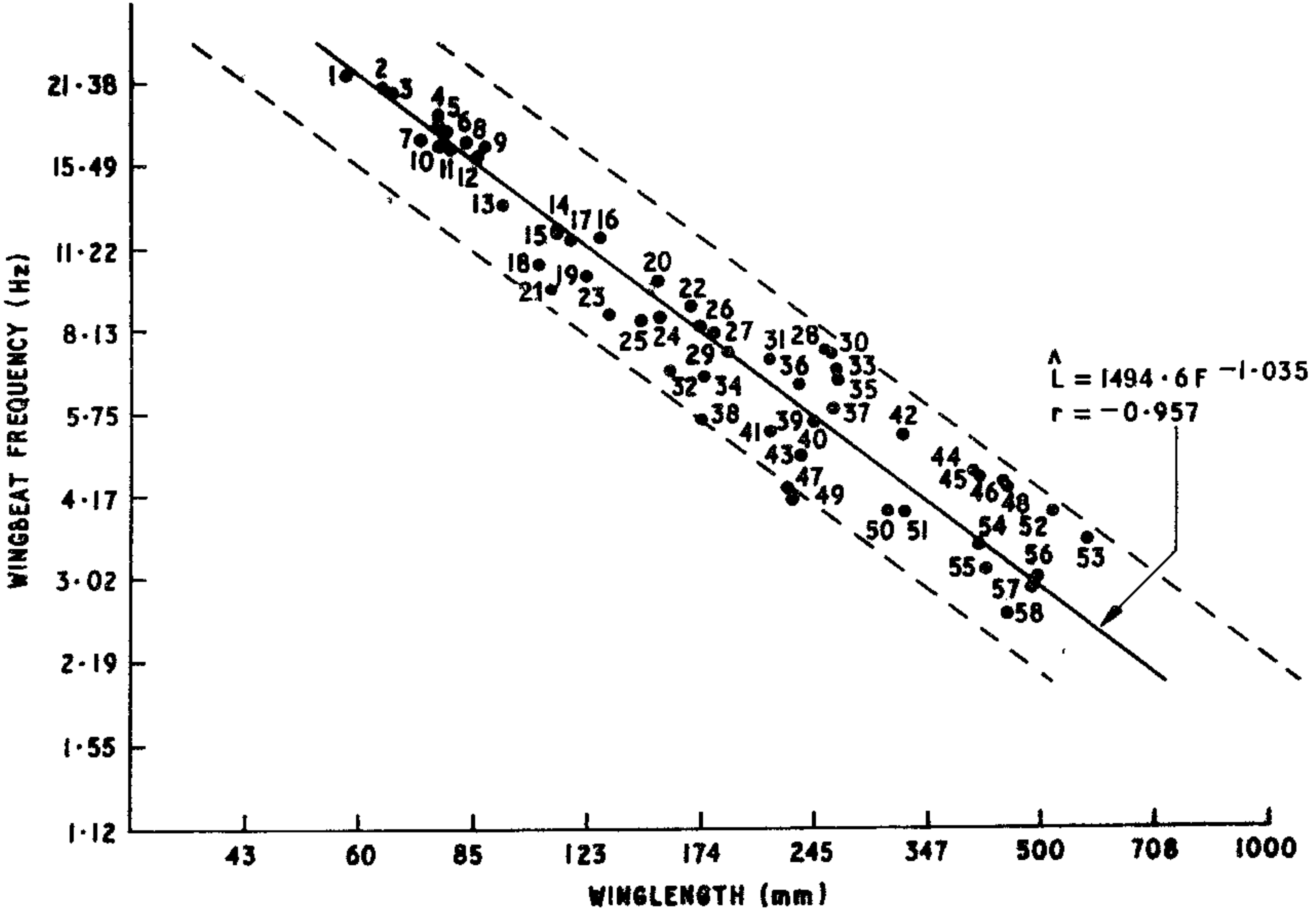


FIG. 6 WINGBEAT FREQUENCY–WEIGHT DIAGRAM

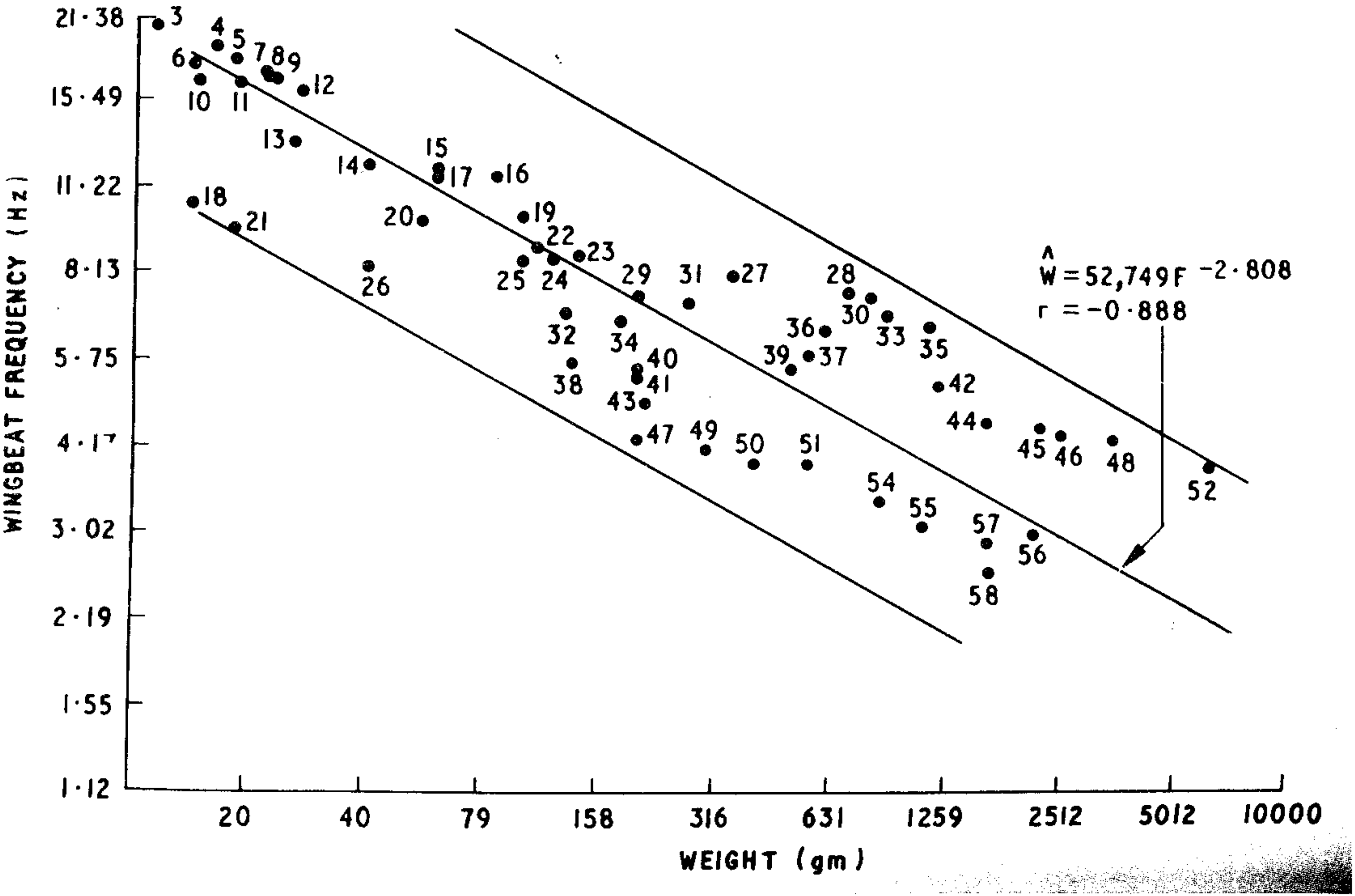


FIG.7 WINGBEAT FREQUENCY – WINGLENGTH DIAGRAM