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HELICOPTER NOISE — BLADE SLAP

Part 2: Experimental Results

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16. Abstract

This is the second of two reports on the topic of blade slap and presents details of the experimental results. The results of the various individual flight tests are presented, and where possible, correlated with one another. Observations from the subjective evaluation of blade slap are included, together with a modified form of the blade slap factor (BSF) which can be used as a design criterion.

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PREFACE

This report outlines the experimental results obtained during blade slap investigations carried out in connection with a N.A.S.A. Helicopter Noise Contract. A previous report (reference 1; NASA CR-1221) reviewed the blade slap topic and presented the theoretical study. In this report it is assumed that the reader is familiar with reference 1.

Since preparation of the earlier report the Blade Slap Factor has been further modified to form a design criterion. This aspect is discussed in Section 8 of this report.

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HELICOPTER NOISE - BLADE SLAP

PART 2: EXPERIMENTAL RESULTS

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ABSTRACT

This is the second of two reports on the topic of blade slap and presents details of the experimental results. The results of the various individual flight tests are presented, and where possible, correlated with one another. Observations from the subjective evaluation of blade slap are included, together with a modified form of the blade slap factor (BSF) which can be used as a design criterion.

1. INTRODUCTION

Blade slap, when it occurs on a helicopter, is the loudest and most objectionable form of rotor noise. At the time of the early stages of this investigation in 1965, severe blade slap appeared to be limited to the two bladed rotor Bell helicopters and the large Boeing Vertol tandem rotor helicopters. With the increase in size of helicopters, blade loading and tip speeds have increased as aerofoils have tended to be worked to their limits and blade slap has become dominant on a wider range of helicopters. Even multi-bladed single rotor helicopters now typically generate noise which is impulsive in nature and is characterised by a mild form of blade slap. Normal operational manoeuvres and descent on the Sea King/SH 3D produce loud blade slap; this is in contrast to the Wessex/S58 which produces only low level intermittent blade slap during normal flight.

This report reviews the various experimental investigations carried out during the period 1965/69 at the I.S.V.R. Although many of these studies are based on individual tests, the results tend to give a clear picture of blade slap and the nature of its generation. From these investigations it appears that, in general, for a quiet helicopter, the blade loading and tip speed should be as low as practicable. Wake distortion and interference effects should also be kept to a minimum, and, thus, on tandem rotor helicopters, the blade overlap should be zero or reduced to a minimum,and the blade separation made the maximum practical.

The various sections in this report describe individual test/experimental programs which are not directly related. For this reason it has not been possible to fully correlate together all the findings, although where possible, cross references to other sections are given. Sections 2, 3 and 4 deal with full scale tests and section 5 an operational survey. Sections 6 and 7 cover blade slap simulation in the laboratory and the subjective assessment of blade slap respectively. A modified form of the BSF(P) developed in reference 1, which can be used as a design criterion, is outlined in Section 8.

2. HELICOPTER TESTS

Flight tests were carried out at Westland Helicopters Ltd., Yeovil; in addition tape recordings were supplied to the I.S.V.R. by Bell Helicopter Co., Boeing Vertol and Sikorsky Aircraft Co. Narrow-band analysis and time history traces were produced from these tapes and used, together with overall levels and dBA levels, to determine the general characteristics associated with blade slap. A representative selection of these results is reproduced in figures 1 to 8 inclusive.

The typical narrow-band analysis results are:-

Figure 1. Belvedere (Internal); V107 (external) and Wessex (Internal).
Figures 2A & 2B CH-46A (external)
Figure 3. UH-1B (external)

The Belvedere analyses are also shown in a slightly different format in figure 14.

Time histories (UV traces) are reproduced as follows:-

Figure 4(a) and (b)	Wessex Mk. 5 (internal)
Figure 5(a) and (b)	Sycamore (internal)
Figure 6(a) and (b)	UH-1B (internal)
Figures 7 and 8	CH-46A (external).

Traces of other helicopters have not been included since they are reproduced in the general literature and/or readily available in company reports.

The tape recordings made of hovering helicopters (tandem) and those obtained in the cabins are fairly constant in level and frequency content, and this produces a 'clean' trace on analysis. The external forward flight results show, as expected, considerable variation with time and hence are more difficult to analyse and interpret. When making the comparison discussed below, as near as possible identical non-slapping and blade slap conditions were examined.

2.1 Accuracy of Recordings.

An examination was made of all the data available at the ISVR to determine if the recordings contained a true representation of the blade slap impulse. The results of this study indicated that in the majority of cases some 'overload' or 'peak' clipping had most likely occurred. In many of the cases, however, it appeared to be only the intermittent 'peak' which was affected and that the recordings were a fair representation of the true levels.

The difficulty which occurs during recording is a direct result of the very impulsive signals produced when blade slap occurs. Typically, the peak level of the impulse is 15/20 dB above the R.M.S. level. Thus when recording, an R.M.S. meter will look effectively 'dead' when the attenuator controls are set at the correct level for recording blade slap. The conventional semi-impulse or 'peak' meter improves the situation; but even so, it is very difficult without the aid of an oscilloscope or special peak level detector, to obtain a true recording of blade slap noise.

It is also possible that the 'peaks' may have been limited to some extent in rise-time by the transient response of the microphone and/or tape recorder. Even allowing for these possible limitations, it was thought that the data was sufficiently acceptable for the particular investigations described in this report. The rise time of the impulse can also be modified by the recording equipment technique used.

2.2 Narrowband Analysis Results

Narrowband analysis was performed using a constant bandwidth analyser system; the appropriate bandwidths and frequency ranges used are shown on the figures. As will be seen, typically a 2Hz. filter was used up to a frequency of 150 Hz, and a 5 Hz. filter beyond this frequency. Although analysis was usually made over the frequency range (10 - 10K) Hz., blade slap analysis was usually curtailed at 3/5 kHz. depending on the helicopter being studied. The amplitude scales are either in SPL re 0.0002 dynes/cm^2, or dB relative to an arbitrary datum.

In general, when blade slap occurs, the corresponding narrow band analysis shows an increase, relative to the non blade slap conditions, in the region equivalent to the 10th/20th blade passing harmonic. Typically, this is in the range 150-400 Hz. Analysis shows that the maximum level of the peak envelope corresponds to the main frequency component of the impulse (see section 6.2).

In addition to the increase of the 'impulse harmonics', the tandem helicopter recordings show an increase in the lower (4th to 10th) blade passing harmonics. This is considered to be an increase in the rotational rotor noise caused by the blade operating in a generally rougher flow environment. This is illustrated in figure 9, which shows the effect on the blade passing harmonics of subjecting a segment of the blade, equivalent to about 1/10th of the disc, to a disturbed flow. The results shown were obtained on the I.S.V.R. 9 ft. diameter single rotor hover model. This effect is further illustrated in the work of Whatmore (2) described in section 6.2. There is also some indication of this effect during the 'high speed' blade slap on the UH-1B (figure 3). In this case it is, however, very much more difficult to correlate the results because of the high levels of low frequency rotational noise present on this helicopter.

2.3 Time Histories - Oscillograms.

It is clear from the traces that the blade slap 'bang' occurs at blade passing frequency; this applied to all the helicopters studied. On the Wessex, Sycamore and Belvedere helicopters the 'bang' approximates very closely to a single impulse (figures 4 and 5). On the UH-1B (figure 6) and the CH-46 (figures 7 and 8), however, the 'bang' consisted of two or three main 'impulses'. This could be the result of blade/vortex interaction occurring over a considerable portion of the blade span at slightly different instants or separate interactions occurring at practically the same time. A study of the traces shows that although the 'bang' sometimes contains several discrete impulses, there is, in general, one impulse which is larger than the others.

To obtain the filtered traces, the recordings were passed through a band pass filter and the signal studied on a CRO and/or UV recorder. The filter pass band limits were adjusted so that the blade slap impulses were not significantly affected while the other noise was reduced to a minimum. The signals were also evaluated subjectively and in each case the characteristic of the 'bang' was found to be unaffected by the filter settings chosen. It is worth noting in this context, however, that the subjective evaluation was made by the helicopter team and a jury was <u>not</u> used. Using the filter reduced the low frequency rotor rotational noise and the high frequency noise which was mainly from the gearbox and/ or engines. This, of course, had the effect of making the 'bang' more readily detected both on analysis and subjectively.

The filtered frequency range associated with the helicopters examined was 50 Hz. to 1 kHz. It is these frequency limits that were used to obtain the 'filtered' time histories shown in figures 4, 5 and 6. 'Non-filtered' refers to unweighted recordings which typically cover the frequency range (20 - 15k) Hz.

The filter ranges were further reduced to isolate, as nearly as possible, the blade slap 'bang'. Although this reduced the amplitude of the impulse, it allowed the main frequency content of the 'bang' to be determined. These frequency ranges are given in Table 1, together with the envelope peak obtained from the narrow-band spectra, (figs. 1 - 3). It seems fair to assume from Whatmore's work (2) that the centre of this frequency band corresponds very closely with the main frequency component of the 'bang'. A review of the results shows that in general this is the case. The envelope peak frequencies quoted in Table 1 were obtained from the average of several narrowband spectra, and not just those reproduced in this report. In the case of Bell UH-1B, CH-46 and V107, it is a little difficult to locate the peak frequency because of the general increase in the rotational rotor noise.

A study of the time history traces also reveals that on both single and tandem rotor helicopters the maximum peak-to-peak levels are increased by approximately 10 dB when blade slap occurs (see figures).

In the case of the UH-1B, however, the blade slap impulse is not so clearly defined and appears to be superimposed on top of the already impulsive rotor noise (figure 6). For this helicopter the peak-to-peak difference between the banging and non-banging modes varied between 10 dB and zero for the various flight conditions studied.

The amplitude scale used on the oscillograms is SPL-dB relative to the standard reference level of 0.0002 dyne/cm^2. The scale is so chosen that a sine wave having an SPL of XdB would produce a sine wave on analysis having an amplitude of ± XdB.

2.4 Overall and dB A Levels.

A review of available data was also made to determine the overall noise level difference between a banging and non-banging helicopter operating as far as possible under similar conditions. The results were rather interesting in that, in general, the addition of blade slap increased the O.A.S.P.L. (dB Lin) and dBA levels by only 2 to 3 dB. In one particular case for a tandem helicopter the difference was as large as 6 dB, but for other cases examined it was as little as 1 dB. However, in the most significant octave band, 250 Hz for most helicopters, larger differences were measured, with the average being in the order of 6 dB. On a narrowband analysis, the level difference at the envelope peak frequency is typically 10 to 15 dB, although in the case of the Sycamore it was only 2 to 3 dB. These differences can be seen on figures 1, 2 and 3.

These general studies have clearly shown that it is not possible to determine the severity of blade slap by considering overall noise levels or octave plots. Even narrow band analysis can give a misleading impression if the general level of rotational noise is high. If results are correlated on a PN dB basis, then it is unlikely that the addition of blade slap will even affect the results. Unfortunately, at the present time, there does not appear to be any reliable method for computing the annoyance or loudness level of blade slap. The use of an impulse level measuring system may, however, offer a solution to this problem. To the author's knowledge this has not been evaluated to date. A possible practical approach would be to add 12 dB to the measured overall dB value to take account of the 'banging effect'. (see section 7.1).

2.5 Discussion of Results.

2.5.1. Tandem Helicopters

(Belvedere, V107 and CH-46A).

On the V107 and CH-46A blade slap occurs in all flight regimes including hover, while on the Belvedere it is limited to forward flight conditions. On the Belvedere, blade slap is usually intermittent and of low level, except in banked turns and mild 'pull-outs' when continuous loud slap occurs. The blade overlap on this helicopter is extremely small, and , in general, it displays blade slap very similar characteristics to a four blade single rotor helicopter. For all practical purposes it would appear, therefore, that the Belvedere can be considered as a four blade single rotor helicopter with two isolated rotors. Although it is not documented, the author has been given to understand that at high forward speed the V107 acts in a similar manner. This is equally understandable since the wake at the 'front' of the rear rotor will either go above, or be at an acute angle to, the rotor disc at high speed, and thus not interact with the lower forward rotor.

The V107/CH-46A has a relatively large area of overlap and produces very loud blade slap. The V107 studied by the ISVR was equipped with a longitudinal trim device that allowed the 'longitudinal cyclic' of the rear rotor, and in effect the blade separation, to be varied. In a steady state flight condition, including hover, the actuation of this trim device substantially strengthened or reduced the severity of blade slap. At moderate forward speeds trimming the V107 helicopter to its most nose down condition increased blade separation and practically eliminated blade slap. In this configuration it is suggested that the rotors are both acting like single rotors and the interaction between the wake of the rear and forward rotor is non-existent. This is very similar to the high speed conditions discussed previously. Figure 7 clearly illustrates the above effect on the CH-46A where the 'trim settings' have been adjusted for maximum and minimum blade slap noise. On the CH-46A, the gains which can be obtained from adjusting the trim settings are dependent on the forward speed and at higher speeds the reduction in blade slap is somewhat smaller. This is shown in figure 8, which shows the 100 knot flight conditions.

A similar situation to that outlined above for the V107/CH-46A also exists on the U.S. Army Chinook Helicopter.

2.5.2. Single Rotor Helicopters

(UH-1B, UH-1D, Sycamore, Scout, Wessex, S 61).

Single rotor helicopters can be grouped into the two categories of 'two-bladed rotor helicopters' and 'multi-bladed' (3 or more) rotor helicopters. These are discussed separately below.

2.5.2.1. Multi-bladed rotor helicopters

A Wessex helicopter was flown in its standard configuration and blade slap was found to occur during the following flight conditions:-

(a) Low power descent
(b) Port and Starboard banked turns of 40^o or more at 60-80 knots.

The blade slap was identical for both the port and starboard banked turns. Intermittent blade slap was also found to occur when any sudden manoeuvre was made and when positive <u>or</u> negative collective pitch was applied. As far as could be determined, when blade slap occurred, it could always be heard simultaneously in the cabin and externally. Similar characteristics are also associated with all the other helicopters studied, except on the Sycamore where a more severely banked turn was often necessary to produce continuous blade slap.

2.5.2.2. Two Bladed Rotor Helicopters

A flight test programme carried out for the ISVR by Bell Helicopters using UH-1B gave some interesting results. Firstly, at low speeds (up to 100 knots), blade slap of the type associated with the multi-bladed single rotor helicopter occurred. Thus banked turns and low power descent produced blade slap. A recent test in London using a Jet Ranger also gave similar results and very loud blade slap was produced during descent.

Very loud blade slap is also produced during straight and level flight at forward speeds around 120 knots. At 90 knots there is no indication of blade slap either internally or externally, while at 120 knots very loud blade slap is detectable externally. At this higher speed condition, however, blade slap could not be heard in the cabin. An examination of recordings revealed practically identical characteristics in the cabin at 90 (no blade slap) and 120 knots (external blade slap), although overall noise levels were a few dB higher. Externally, the noise showed a considerable change both in level and characteristics. Bell (3) associate this 'high speed blade slap' with the onset of compressibility effects on the advancing blade and the occurrence of local supersonic flow. The details of the noise generating mechanisms are not known, but Bell do not think it is the blade/vortex interaction type of noise which occurs at low speeds and during low power descents. A detailed examination of recordings of both blade slap conditions has not shown any characteristic difference, but this is not surprising since any impulsive mechanism would produce a similar acoustic signature. This is discussed further in reference 1.

3. FORWARD FLIGHT TESTS

Location of Blade Azimuth Position when Blade Slap occurs

In an attempt to locate the rotor azimuth positions when the blade slap 'bang' occurred, a series of flight tests were carried out by Westland Helicopters Ltd. The single rotor helicopters used were a Sycamore (3 bladed rotor) and a Wessex (4 bladed rotor).

A forward flight speed of 65 knots (≃ 110 ft/sec) was selected for these tests, since with the helicopters used, blade slap could be conveniently generated at this speed. On the Wessex it was necessary to fly in a 40/45° banked turn before continuous blade slap of a relatively loud level was produced, while on the Sycamore an even larger bank angle was required.

Simultaneous recordings of the noise in the cabin, at a known position, and a signal from a blade azimuth marker on the rotor head were made on a twin track tape recorder. The recordings were subsequently played back through a UV recorder and traces of blade slap and azimuth position obtained. Since blade slap occurs at blade passing frequency, four and three blade slap impulses were obtained per rotor revolution for the Wessex and Sycamore respectively. The rotor head orientation at the instant the 'bang' was measured acoustically could be fixed from these traces. To determine the blade position at the moment of blade slap it was necessary to take into account:-

(a) the time taken for the impulse to reach the microphone, and
(b) the blade lag relative to the rotor hub.

It seemed reasonable to assume that the 'bang' occurred near the tip. Initially this was assumed to be at 0.95R in which case the blades would have moved on the Wessex a further 34° before the signal reached the microphone. The blade lag of 5° was obtained from standard flight data for the condition flown. These angles are illustrated for the case of the Wessex in figure 10, together with the estimated position of the blades when the 'bang' occurred. The 33° increment, equivalent to the interval between the azimuth marker 'blip' and the recorded blade slap signal, was the average of 10 rotor revolutions. The results were, as expected, very consistent, and within the measuring accuracy (better than ± 1%) the blade slap impulse occurred at blade passing frequency. Using the approach outlined above, the blade positions when the 'bang' occurred for the Wessex and Sycamore are those shown diagrammatically in figures 11(a) and 12(a) respectively. Although the rotor rotation on a Sycamore is clockwise (as viewed from above), the result has been converted to an anti-clockwise convention for comparison with the Wessex.

The theoretical blade bang azimuth position was calculated using a simple rigid wake model, even though recent work on the wake patterns associated with single rotors has shown that the wake shapes are likely to be much more complex (5, 6).

The experimentally measured results were correlated with the predicted 'bang' positions obtained using the following approach: When the trailing wake leaves the rotor tip it combines into a strong 'tip vortex' which moves inboard. Hover results show that the tip vortex can quickly move into a position which is equivalent to the 0.9R station. In forward flight the contraction is considered to be less, and the tip vortex is more likely to take up a position just after leaving the blade which corresponds to 0.95R. Limited experimental evidence to date does, however, suggest that the contraction of the wake is greater at the sides (90° and 270° regions) than at the front and rear of the rotor. Because of the lack of precise knowledge on this point, for this particular study predictions were made for a range of values between 0.9R and 0.95R.

The results for the Wessex and Sycamore are shown on figures 11b and 12b respectively. As can be seen, the 'bang' is assumed to occur at the position where the tip of a blade intersects the trailing vortex wake left by the proceeding blade. A comparison of the measurements and predictions shown on figures 11 and 12 show that there is good correlation, particularly in the case of the Wessex. Even in the case of the Sycamore the difference between the 0.9R predicted position and the measured position is only 12°, which is surprisingly good when all the variables in estimating the rotor blade position and the limitations of the simple rigid wake model are taken into consideration. In this context it should be remembered that it is not possible to take into account the fact that the helicopters were banked to obtain blade slap. On the other hand it is well known that the vortex filament stays in or near the rotor disc until the next blade approaches (see section 4), when vortex distortion effects become significant. Thus a simple wake approach can be expected to give at least an indication of the blade position when the 'bang' occurs, if this is produced by the first blade/vortex interaction.

Since the above tests were performed, Boeing Vertol (4) have reported an extensive blade slap flight programme carried out on a tandem rotor helicopter. They showed clearly that the 'bang' occurs when a blade intersects a tip vortex and that a simple rigid wake could be used for estimating the magnitude of the bang and blade azimuth position at which it occurs. It is also of interest to note that the experimental results do not in any way agree with Sikorsky findings (7) that the 'bang' occurs on the retreating blade at the 270° position.

On the Wessex, identical results were obtained for both starboard and port bank turns, but this aspect was not examined on the Sycamore.

4. TIP VORTEX PATHS

In reference 1 a photograph of a Westland Westminster showing the tip vortex filaments as condensation trails was included. Some equally interesting photographs were obtained by Westland Helicopters Limited, Yeovil, on a Sea King (British built Sikorsky SH-3D). Two of these photographs are reproduced in plates 1 and 2. The Helicopter was hovering in a light wind, estimated to be 10 to 15 knots, and the photographs were taken from above and to the side. In each case the trailing filaments pass above the following blade before descending below the rotor disc. In the flight mode shown the Sea King does not produce any blade slap, but the general rotor noise is more impulsive in nature than that produced by the other Westland helicopters. Although other helicopters, including a Wessex 60 (partly shown in the photographs), were flying at the same time as the Sea King, condensation trails were not seen. To date it has not been possible to explain this phenomenon. It was initially thought that it might be correlated with blade loading or ideal vortex strength but this proved negative. The only parameter having a significant difference was the loading per blade which was greatest for the Sea King but it is difficult to see how this can offer an explanation. It is tentatively suggested that the spanwise loading distribution, and hence the 'true vortex strength' may be different on the Sea King and account for the appearance of the vortex filament.

5. OPERATIONAL SURVEY

(Military and Civil)

During 1965/66, Mr. F.W. Taylor* carried out a comprehensive operational survey throughout the United States and the United Kingdom; this included all the Armed Services and the majority of helicopter manufacturers and operators. The observations outlined below were obtained from this survey, which is discussed in greater detail in reference 8. Further information, which has become available since the date of this survey, has tended to agree with these general findings.

The Blade Slap problem is primarily one of civilian public relations and military operational tactics. All pilots could recognize blade slap, and most preferred not to fly in that condition. Blade slap can, at least to some degree, be found on virtually every type of helicopter, although some are far more susceptible to it and the noise more severe. Blade slap usually occurs during transient manoeuvres, but in some models such as

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*U.S. Army Research Fellow at I.S.V.R. during year 1964/65.

the Iroquois and Chinook, continuous blade slap can occur in level flight. Blade slap is often associated with turns, with shallow descents, and with flare approaching a hover.

In addition to the above, pilots associated blade slap with high altitude, high temperature and high gross weight. Descents (either high or low speed), together with steep bank turns (45° or more) are specific flight conditions associated with blade slap. Autorotation entry at high speed and level flight at low speed were also identified as regimes often producing blade slap. Internally the banging noise is classed as irritating, fatiguing and annoying; in this context the duration of crew exposure is an important factor.

It is of interest to note that many of the above conditions are those when the inflow ratio is near zero. On the British designed Gyrodyne*, which was designed to fly with zero inflow ratio, continuous blade slap was encountered in cruise.

Virtually everyone surveyed agreed that, on a given helicopter, increasing the load factor increased the severity of blade slap. During let down, moderate rates of 500 to 900 ft/min appear to produce the worst conditions. Decreasing collective pitch for descent, or increasing collective pitch for more positive load factor or greater speed, can both produce blade slap.

Helicopter vibrations often increase with the occurrence of blade slap, but there does not appear to be any direct correlation between blade slap and airframe vibrations.

6. BLADE SLAP SIMULATION

6.1 Investigation 1.

The general test arrangement used for the initial ISVR blade slap simulation (9,10,11) is shown in figure 13. As can be seen, a twin air jet system was used to simulate a tip vortex. The distance between the air jets and the air pressure were adjusted to give the same type of velocity profile as expected from a real tip vortex. A comparison

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* This compound helicopter, with augmented thrust and off loaded rotor, should not be confused with U.S. Gyrodyne with a co-axial rotor configuration.

between real helicopter blade slap and the simulated blade slap in terms of narrowband analysis and oscillograms is shown in figures 14 and 15 respectively. The similarity between the real and simulated blade slap is clearly illustrated.

A theoretical study of the generation of sound due to an impulsive loading of the blade-slap type (1,10) gave the following relationship between the Sound Pressure Level (SPL) and the gust input loading parameters.

$$\begin{aligned} SPL_n &= PWL_n \text{(Sound Power Level)} + \text{const.}, \\ &= 10 \log_{10} \left[V^4 . A_n^2 . (r_o - r_1)^2\right] + \text{const.}, \end{aligned} \qquad 6.1$$

where SPL_n is the SPL of the n^{th} blade slap harmonic (shown on the narrowband spectrum analysis trace);

V is the velocity of the blade passing through gust;

A_n is the amplitude of the n^{th} harmonic of the time history of the blade upwash velocity;

$(r_o - r_1)$ the span width over which the gust acts.

It was necessary to consider the blade slap harmonics separately, since the narrowband analysis also contains rotational noise harmonics. The harmonics due to the blade slap impulse (gust) were determined by comparing the rotor noise traces with and without the blade slap impulse.

Figures 16 and 17 show the general type of agreement obtained which confirmed the theoretical approach. The effect of $(r_o - r_1)$ could not be studied with the air jet arrangement used.

When the position of the air jet was moved along the blade span some surprising results were obtained - these are shown in figure 18. Theoretically the variation should have been that caused by the effective decrease in blade velocity and the slight change in impulse characteristics as the gust is moved along the span towards the hub. The former varies as R_G^2, where R_G is the radius at the gust centre, while the latter cannot be accurately estimated. However, since the effect of altering the velocity is largest, the R_G^2 law or V_G^4 law can be assumed to apply. Figure 18 shows two clear trends. Firstly, a 'fall-off' relative to the theoretical values as expected, occurs near the tip where the blade cannot sustain lift. The maximum value occurs at approximately 85% radius, which is roughly the position where the blade would experience maximum steady aerodynamic loading. Secondly, there is an increase in noise around the 96/97% radial position. A plot of 1/3 octave band and octave band results are included in figure 18(b), together with the 15th harmonic to show that it is a general trend and not due to any predominant harmonics. Although this cannot be satisfactorily explained, it is thought to be the result of an interaction of the impulse (gust) and an induced tip vortex.

Another interesting result is illustrated in figure 19, which shows the variation of SPL with pitch for a constant gust input. This shows that although the normal rotational rotor noise increases with pitch, the blade slap levels are unaltered. This is in agreement with the theory which shows that the blade slap noise is dependent only on the square of the rate of change of the loading (8).

Using equation 6.1, the power in each noise harmonic was calculated and compared with values obtained from sound pressure level measurements. A typical result is shown in figure 20 and as can be seen there is a good agreement both in shape and amplitude. Although for the case shown the measured values are 3 to 5dB above the theoretical results, the difference between the two power curves varied between + 11dB to -5dB for the complete range of conditions studied. A detailed study was also made of impulse characteristics and it was found that the 'shape of the bang' varied considerably even under controlled laboratory conditions. Figure 21 shows oscillograms which illustrate the range of impulse shape variations. The theoretical 'bang' signature for the condition illustrated in figure 21 is reproduced in figure 22 together with a typical measured impulse. Although a direct comparison between the amplitude of the two results is not possible, the overall shape and pulse duration show good agreement.

6.2 Investigation 2

A study of helicopter rotor transient noise, with particular reference to blade slap, was recently carried out at the ISVR by Whatmore (2). In this he simulated the blade slap impulse and superimposed it onto a recording of a Wessex helicopter operating without blade slap. He then compared the results of various analyses with a recording of the same helicopter operating in a blade slap mode. He found that the best representation for a Wessex type blade slap was a single sine wave cycle of 200Hz. A review of other helicopter recordings showed similar results, but it is possible that a slightly more complex form may be desirable for the simulation of blade slap on some helicopters. Even so, the difference between the single sine wave approach and the 'true' impulse would be expected to be very small.

One point of interest was that it is impossible to put a single cycle of a 200Hz sine wave repeating at a typical blade passing interval, on to a Nagra (direct recording) tape recorder without severe distortion. The distortion was so bad, in fact, the signal was unrecognizable. This is a significant factor, since Nagra tape recorders are commonly used to record blade slap. The situation in practice may not, however, be quite as serious since the 'bang' impulse is added to an already existing noise signal which contains similar frequencies.

The isolated impulse and 'helicopter noise + impulse' were analysed using a Spectral Dynamics Analogue Analyser System and also on the ISVR Data Analysis Centre's analyser. This latter unit is based on a Myriad Computer and although it takes analogue data it converts it to digital form for processing. An analogue output in the form of a chart is available. In addition to the above, the frequency components of the impulse were found by using basic Fourier mathematics.

Errors are inherent in the analysis of impulses on an analogue system and in this case the accuracy decreased above 200Hz although significant errors only occurred above 400Hz. It is of interest to note that these limits agree well with the findings of Quinn and Thomas (12) where the various parameters most likely to produce such errors are discussed in detail.

The narrow-band analogue analysis results are shown in Figure 23 and the digital analysis of the impulse waveform in figure 24. With regard to the latter it will be observed that the 'base' noise on the tape recorder as illustrated in the upper part of figure 24 has a significant effect on the higher frequency components. The input was 'cleaned up' by making the digital input zero except in the region of impulse. In this case, of course, a true representation of the mathematical solution was obtained. It will be observed that there is general agreement between the real and simulated blade slap cases. The only real difference is that the simulated blade slap analysis (Fig 23 - trace C) contains more high level harmonics in the region 120 to 160 Hz, than the real blade slap analysis (trace B). This can not be accounted for in detail, but it is considered that the dip in the spectrum of the real helicopter recording is most likely due to signal cancellation at the microphone.

The simulated results indicated that the maximum harmonic component (at 200 Hz) should be 22dB below the peak level of the impulse. Figure 4 shows time histories (oscillogram traces) of the Wessex cabin noise. For the 'filtered trace' shown the signal has been filtered as explained in section 2.3; this clarified the blade slap impulses without any significant reduction in the amplitude. The average peak-to-peak value of the impulse is about 130 dB. Thus analysis of the tape used to produce the oscillogram should give a trace with a maximum harmonic content at 200 Hz of 108 dB (130 dB - 22 dB). Trace B on figure 23 shows a maximum value of about 106 dB, indicating that the experimental results are about 2dB lower than the theoretically predicted value. This small difference is probably a result of the combination of errors in the analogue output and the large variation in the blade slap impulse amplitude (as seen by inspection of figure 4).

To investigate if blade slap can always be detected on a narrowband analysis, the simulated impulse was added to the helicopter noise at various levels. Figures 25 and 26 show the oscillograms and narrowband analysis results respectively, related to this study. As the impulse level, relative to the helicopter noise, is reduced the impulse becomes more difficult to detect on the narrowband analysis traces. When the impulse is just audible, then it is just detectable (figure 26 trace B). At lower levels the 'peaks' disappear from the analysis and the impulse is subjectively no longer detectable as blade slap, and, in the practical case, would merge with the general impulsive rotational noise.

Although it is not immediately applicable to blade slap, the difference between subjecting a rotor to impulsive loading (short gust) and a stepped rectangular shape gust was examined. The result of gradually increasing the gust length is shown in figure 27. The number of nozzles quoted on the figure corresponds to the length of the gust. 1 nozzle gives a gust length of about ½ chord, and 24 nozzles a length of just over 6 chords. On the model used, 1 chord is 4 inches. From the short gust case where the analysis is similar, as expected, to the blade slap case, the spectrum changes until the increases are confined to the low frequency rotational harmonics. These results agree qualitatively with the Fourier analysis of the gusts applied to the blade (2).

Two general observations are that narrowband analysis has to be used with care for the study of blade slap, and that above 200 Hz. care must be taken to ensure that the analogue trace is a true representation of the recorded signal.

6.3 OBSERVATIONS AND CONCLUSIONS

The simulated blade slap gave the same acoustic signature as that associated with actual helicopters. This combined with flow visualization tests on a similar model rotor at the ISVR tends to confirm the blade/vortex interaction model for blade slap, as at least one of the main mechanisms which generates blade slap. In this context it is interesting to note that such simple model experiments can give valuable information. Full scale tests on similar lines, although costing many magnitudes more, have not in general given much more information towards the basic understanding of blade slap generation.

If the equation developed for the experimental investigation is modified to give the total power (noise) of the 'bang', the parameters relating to real helicopters can be derived. This is discussed in reference 1 and results in the following relationship.

$$BSF(P) \propto V^4 . \Gamma^2 \qquad 6.2$$

where BSF(P) is the power of blade slap impulse,

V is the blade velocity,

Γ is the vortex strength.

The above relationship is essentially the same as equation 6.1 with $\sum A_n$ replaced by the vortex strength Γ. In deriving this relationship all the other parameters are, of course, assumed to remain constant.

Equation 6.2 indicates that the noise increases with the square of the vortex size or strength. This is an important result, since it implies that helicopters with highly loaded blades are more likely to produce loud blade slap than those with light loading. This is obviously an important parameter when considering the Iroquois helicopter, which in spite of its light weight has a vortex strength 30% greater than that of the Wessex.

The noise produced by a blade passing through a vortex of fixed size varies as V^4, where V is the velocity of the blade. Thus on a helicopter, with the vortex strength proportional to V , (see Reference 1, section 7), it is likely that the amplitude of 'blade slap' noise is proportional to V^6. This is not a significant factor on most helicopters since they usually operate with the same order of tip speeds. It could, however, be a contributing factor on the Bell range of helicopters, with rotors operating at high tip speed.

The experimental results have also indicated that blade slap noise is independent of the pitch angle of the blade. This means that in practice the pitch is only important in that it affects the loading and therefore, the vortex size.

Whatmore's investigation (2) confirmed that the nature of blade slap is, in general, a single repetitive impulse and showed that although the energy content of the 'bang' is small in comparison with the overall helicopter noise energy it is capable of being detected on a narrowband analysis. It was also found that provided the blade slap impulse is subjectively detectable, then it is also easily observed on a narrow band analysis (5Hz bandwidth).

The experimental study confirmed that a short gust (rapid change in lift) produced peaks on a narrowband spectrum in a frequency range comparable with the time taken for the blade to pass through the gust. As the gust length is increased substantial increases occur at the lower end of the frequency spectrum. When the gust length is several times the blade chord the noise spectrum is very similar to that for a blade passing through general turbulence, as illustrated in figure 9.

7 SUBJECTIVE ASSESSMENT

An attempt has been made to evaluate the subjective effects of blade slap and the applicability of the BSF(1) for rating blade slap.

Unfortunately, although some interesting trends have been obtained it has not been possible to check in any depth the accuracy of the BSF approach because of the lack of reliable data.

The work to date has been in two main areas:-

1) The subjective comparison of the loudness and annoyance of a 'banging' and 'non-banging' helicopter;

and

2) A study of the effect of the impulse shape and duration on the subjective loudness.

7.1 Comparison of the Loudness and Annoyance of a 'Banging' and 'Non Banging' Helicopter

In order to gain information on the subjective effects of blade slap a limited series of tests were carried out at the ISVR, For this study it was assumed that the data supplied by some helicopter manufacturers was a true representation of the blade slap 'bang'. (See section 2.1).

The main object of this study was to determine the increase in loudness and annoyance associated with the occurrence of blade slap on a helicopter.

A small jury of trained listeners was asked to compare the loudness of a 'banging' and non-banging' helicopter (as recorded out of doors) in the following environments:-

(a) in the open, well away from walls,

(b) in a semi-reverberant room, equivalent to a large well furnished lounge,

(c) in a small reverberant office (size 12 ft x 9 ft x 10 ft high).

The measured difference between the 'banging' and 'non banging' helicopter was 5 to 6 dBA.

In the above tests the 'banging' helicopter sounded louder than the 'non-banging' one by 6 dBA, 7dBA & 8dBA inlocations (a), (b) and (c) respectively.

In the second part of the experiment to determine the annoyance, light music was played simultaneously with the helicopter recordings. The tests were carried out in a semi-reverberant room (location 'b') with the music at a level of 77 dBA and the helicopter recordings set initially at a level of 63 dBA, i.e. 14 dBA below that of the music. In the light of a previous survey the levels chosen for these tests were considered to be representative of the noise levels experienced in a house near, or under, helicopter flight paths. A jury and individuals were asked to adjust the 'non-banging' helicopter recording to a level where it was, relative to the music, equally as annoying as the 'banging' recording. On average, the 'non-banging' case was adjusted to a level 6 dBA above that of the 'banging' case for equal annoyance. There was a large variation in results with one person stating that the 'banging' case was not at all distracting, while another rated the difference at 14 dBA. 60% were, however, in the range 4-8 dBA. It is of interest to note that this type of variation in results is usual when judgements depend on individual interpretation of annoyance.

The above results indicate that the 'banging' helicopter would have to be four times as far away as the 'non-banging' helicopter, in order to sound equally annoying. This corresponds to a 12 dB reduction in level, 5-6 dB to equalize the dBA ratings and a further 6 dB as indicated by the annoyance experiment.

7.2 Effect of impulse shape and duration on loudness

In developing the BSF in reference 1, a generalised form of the blade loading curve was used and it was shown that:-

1) in terms of the 'power' and 'energy' of the impulse sound only the first harmonic of the gust (a single sine wave) was important; and

2) the amplitude W_1, of the first harmonic could be taken as equivalent to the peak amplitude W of the gust velocity.

The above approach resulted in the approximate solution for the BSF being in the order of 1.7 less than that which would be otained using the exact solution (see figure 14 reference 1). The form of the exact (curve B) and approximate (curve A) impulses is shown in figure 28. The points used in the computation, described in the following sections, are indicated on the figure by an 'x'.

At the time of this particular investigation, and to the authors knowledge even at the present time, it is not possible to calculate the loudness of a series of impulses. Thus the study was limited to estimating the loudness associated with a single blade slap impulse. It was considered, however, that the general trends of the single impulse are equally applicable to the repetitive impulse case and thus worth investigating.

The time scale for the impulse was chosen such that it was typical of blade slap, with the total pulse duration (3 time units of the time scale shown on figure 28) being equal to 2.4 m sec. The loudness in terms of Phons was computed for:-

(a) amplitude scale of B ≡ amplitude scale of A

(b) amplitude scale of B ≡ 2 x amplitude scale of A

In the prediction process, described in reference 13, it is necessary to fix the amplitude of the impulse in absolute units. A 100 dB level (Phon Curve) was used for the derivation of the term $k|F(\omega)|^2$ (see reference 13). The 'k' is a weighting factor for the frequency sensitivity of the hearing mechanism, which in this case is the conversion for the equal loudness phon weighting. This level was chosen as being representative of the levels experienced by personnel in the vicinity of helicopters producing blade slap. The results were as follows:-

Loudness -	Approx. Impulse - A	Loudness Exact Impulse B
Condition (a)	108 Phon	104 Phon
Condition (b)	108 Phon	109 Phon

Condition 'b' corresponds very closely to the results of the method used in reference 1 in the derivation of the B.S.F. From this it can be seen that the simplified approach gives a solution very close to the exact value. It is also of interest to note that this agrees well with the simple energy correlation discussed in section 7.3 of reference 1.

The second part of this study involved using the exact solution and determining the effect of pulse duration on the loudness. A range of pulse durations from 0.9 m sec. to 6 m sec. were used and the results are summarised on figure 29. It will be observed that as the pulse duration is initially increased there is an increase in loudness. When the pulse duration exceeds the order of 3 m sec, however, the loudness becomes practically independent of pulse duration.

A study of the time histories associated with blade slap reveal that typical bang durations vary from 3 - 6 m sec. It would be reasonable to assume, therefore, that for all practical purposes the loudness is independent of the type (pulse duration) of the impulse.

If, however, the slap duration is dependent on the blade chord, (as suggested by the BSF(E) - Impulse energy approach in reference 1), there may be some advantages in having small chord rotor blades.

8. BLADE SLAP FACTOR (BSF) CRITERION

In an attempt to predict the severity of blade slap likely on any rotor, a Blade Slap Factor (BSF) was developed at the ISVR (1). Because precise details of the tip vortices are not available, it was necessary to use a number of assumptions in deriving the final relationship , which gives the power of the 'bang' in terms of the parameters.

The BSF based on the power of the impulse is given by:-

$$BSF\ (P) = \left[\frac{V_T . T}{RB} \right]^2$$

where V_T = blade tip speed ft/sec

T = Total thrust - AUW lbs.

R = rotor radius - ft.

B = No. of Blades.

In deriving this relationship, it was assumed that blade vortex intersection occurred in the least favourable form, i.e. the blade cuts directly through the centre of the vortex.

The above formula can be re-arranged as follows:-

$$BSF(P) = V_T^2 . L^2$$

where L = Blade Span Loading - lbs/ft.

The data used in (1) has been re-examined, together with some additional information, and a BSF(P) Acceptability Criterion established. This is illustrated in figure 30, but because of the scatter of results a 'band of values' has been chosen in preference to one specific value.

As shown on figure 30, this criterion implies that blade slap would become very loud and unacceptable if the BSF(P) value exceeded the range 700-900 x 10^7. When using this approach it must be remembered that it predicts the least favourable condition, i.e. the maximum blade slap noise possible, and does NOT imply that blade slap will necessarily occur. The Mil 10 and CH-53D (S65) both have large BSF(P) values but do not produce significant blade slap.

This is accounted for by the fact that, on these and other multi-blade single rotor helicopters, the type of blade/vortex interaction associated with two bladed rotor and tandem rotor helicopters is unlikely to occur. A study of possible blade vortex intersection patterns shows that as the number of blades on a rotor is increased there is less likelihood of the theoretical case, considered in developing the BSF(P), being realised. From a simple study of possible blade/vortex interactions for a single rotor helicopter, it can also be seen that the magnitude of the lift fluctuation, and hence the noise, increases with increasing flight speed. Thus medium-high speed manoeuvres on conventional single rotor helicopters tend to produce louder blade slap than those associated with near hover conditions. This also explains why the level of blade slap associated with a whirl tower is lower than indicated by the BSF. In this case, the blade/vortex interaction is associated with the non-uniform flow induced by re-circulation and wind effects. Thus the BSF criterion can be expected to be over-restrictive for single rotor interactions which could occur in hover or slow forward flight.

8.1 Boeing Vertol Criteria

Boeing Vertol have established 'slap' and 'rotational noise' criteria for a single three bladed CH-47 rotor in hover (14,15). The blade slap criterion is reproduced, from references 14 and 15, in figure 31. Although the original Boeing Vertol data was presented on a linear scale graph, a 'log-log' format has been chosen for the figure since the criterion is then a straight line.

The Vertol criteria were established from the results of a listening jury who were presented with the noise of the rotor for a wide range of span loadings and tip speeds, and asked to rate the acceptability of the sounds. Very few details of the tests are available but it is stated that 80% of the subjects rated the noise unacceptable above the range shown in figure 31.

The frequency range of the data was (200-20K)Hz, and hence the low frequency rotational noise was not included in the subjective evaluation. It is not possible to verify if this is a significant factor, but intuitively, it would be expected to affect, at least, the lower tip speed results. Some recent work at the ISVR (2), with specific reference to a Wessex, has shown that considerable energy occurs in the 200Hz region and that the 'cut off' frequency should not be set above 120Hz. Some analysis performed previously at the ISVR on the Chinook (2 x 3 Blades) also revealed similar results, but since there is no further information available, on the CH-47 Whirl Tower test, it is not possible to investigate this aspect in any detail.

8.2 Comparison of the Boeing Vertol Criteria and BSF(P) Results

The 'slap criterion' obtained by Boeing Vertol takes the form $V_T^2.L$

(L = Blade Span Loading) and it is stated that this result is obtained from a simplified derivation for constant SPL from a blade vortex intersection. The BSF(P) discussed previously, however, results in a $V_T^2L^2$ law for a particular rotor. Details of the derivation of the relationship are not presented by Boeing Vertol and thus it is not possible to establish the reason for the difference.

The BSF(P) has been converted into the format used by Boeing Vertol. A direct comparison of the two criteria is given in figure 31. It will be observed that, over the helicopter operating tip speed range shown, the difference in the slopes of the two curves is not a significant factor but the Boeing Vertol values are 2 to 3 times larger than the BSF(P) criteria.

It would be expected that any results obtained using a whirl tower would suggest a higher criterion than the BSF factor given here, since the severe form of blade slap associated with the tandem rotor helicopters, and forward flight of single rotor helicopters, is unlikely to occur on a whirl tower. It is not known how Vertol carried out their tests, but it is thought that natural wake distortions, due to the presence of the whirl tower, and wind effects, were used to induce blade/vortex intersection. If this was the case, then the Boeing Vertol results would apply to low forward speed interaction effects, while the BSF criteria would be more appropriate to moderate and high speed flight conditions.

Values relating to a number of helicopters have been calculated and these have been included in figure 31. The unrealistic nature of the Vertol criterion, for general application, is clearly illustrated in the case of the Bell helicopters (UH-1B; UH-1D) and the Boeing Vertol Chinook (CH-47B) which both produce very loud blade slap. It should be noted, however, that the Boeing Vertol criterion is only stated to apply to a single rotor.

8.3 Use of the BSF Criterion

The BSF criterion can be used in the design stage to give a 'feel' for the likely magnitude of blade slap. If the suggested limits are exceeded, then a detailed study should be made to determine the possibility of blade/vortex interaction. It should be remembered that the BSF will predict the least favourable case, and except in the case of tandem helicopters, the actual noise would most likely be lower than indicated. It may be extremely difficult to determine if blade/vortex interaction would occur since this is dependent on a large number of variables including crosswind, and blade/fuselage interference, and, of course, the changes in rotor operating parameter necessary for control. In this latter context it is worth noting that on a conventional large multi-bladed single rotor helicopter, blade slap is usually induced only in 'low power descents' and manoeuvres. Theoretical methods are not yet available to allow the actual vortex paths to be predicted in detail and it is suggested, therefore, that the best approach would be to carry out flow visualization studies using a model rotor in a wind tunnel.

Taking into account the limitations of the BSF method, it agrees reasonably well with practical results, except possibly in the case of large multi-bladed single rotor helicopters. Even for this latter type of helicopter there does appear to be general agreement between the blade slap noise and the criterion if severe blade slap is induced.

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TABLE 1 - BLADE SLAP ENERGY LIMITS

Helicopter	FILTER FREQUENCY LIMITS		Envelope 'peak' freq from N/B Traces, Hz.
	Frequency Range Hz.	Centre Freq. Hz.	
Wessex	120 - 270	195	200
CH-46A	190 - 380	285	275
V107	120 - 480	300	230
Bell UH-1B	90 - 320	205	250
Belvedere	80 - 320	200	170
Sycamore	120 - 450	285	220
S61	120 - 480	300	-

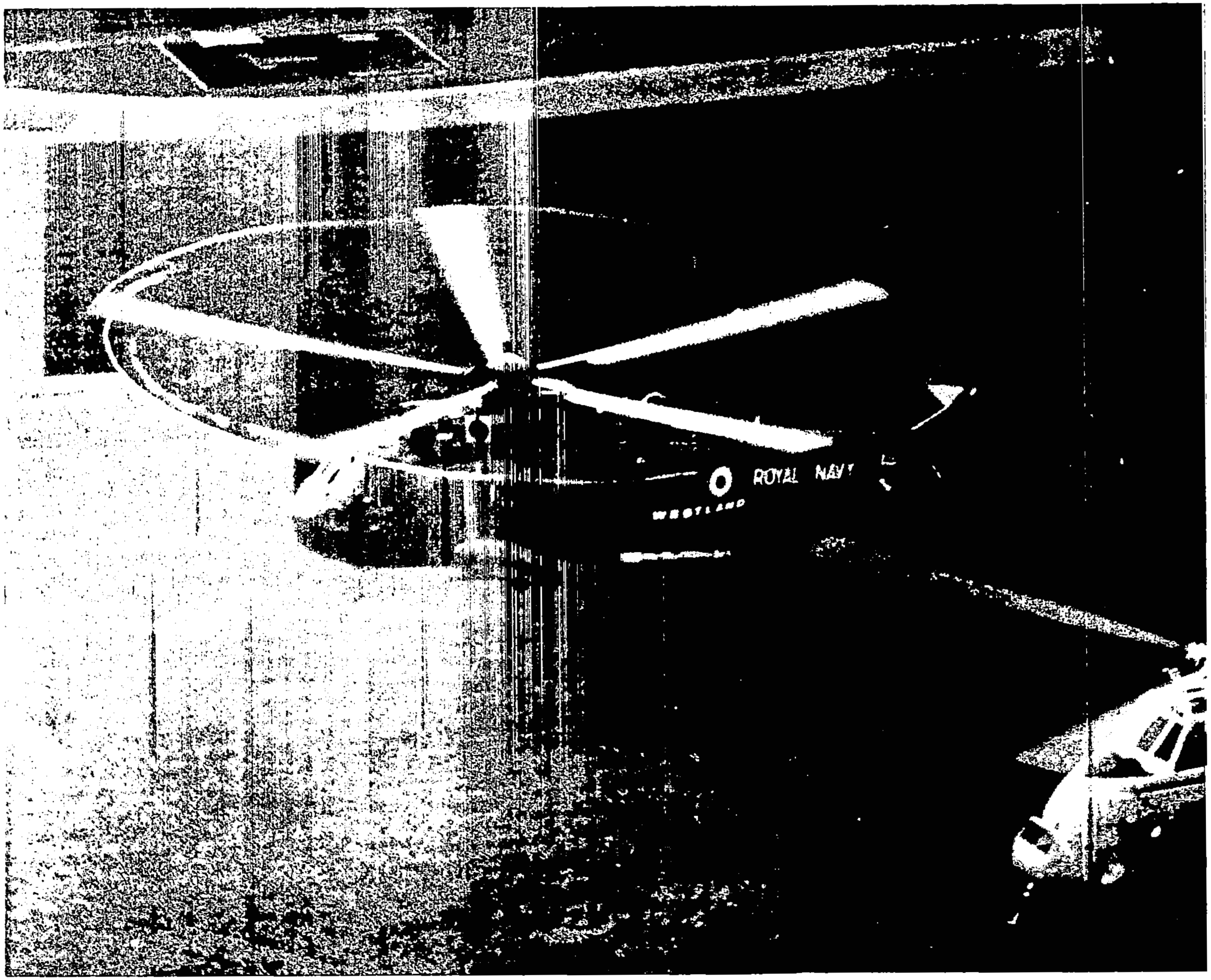


Plate I. Photograph of hovering Sea King showing tip vortices.

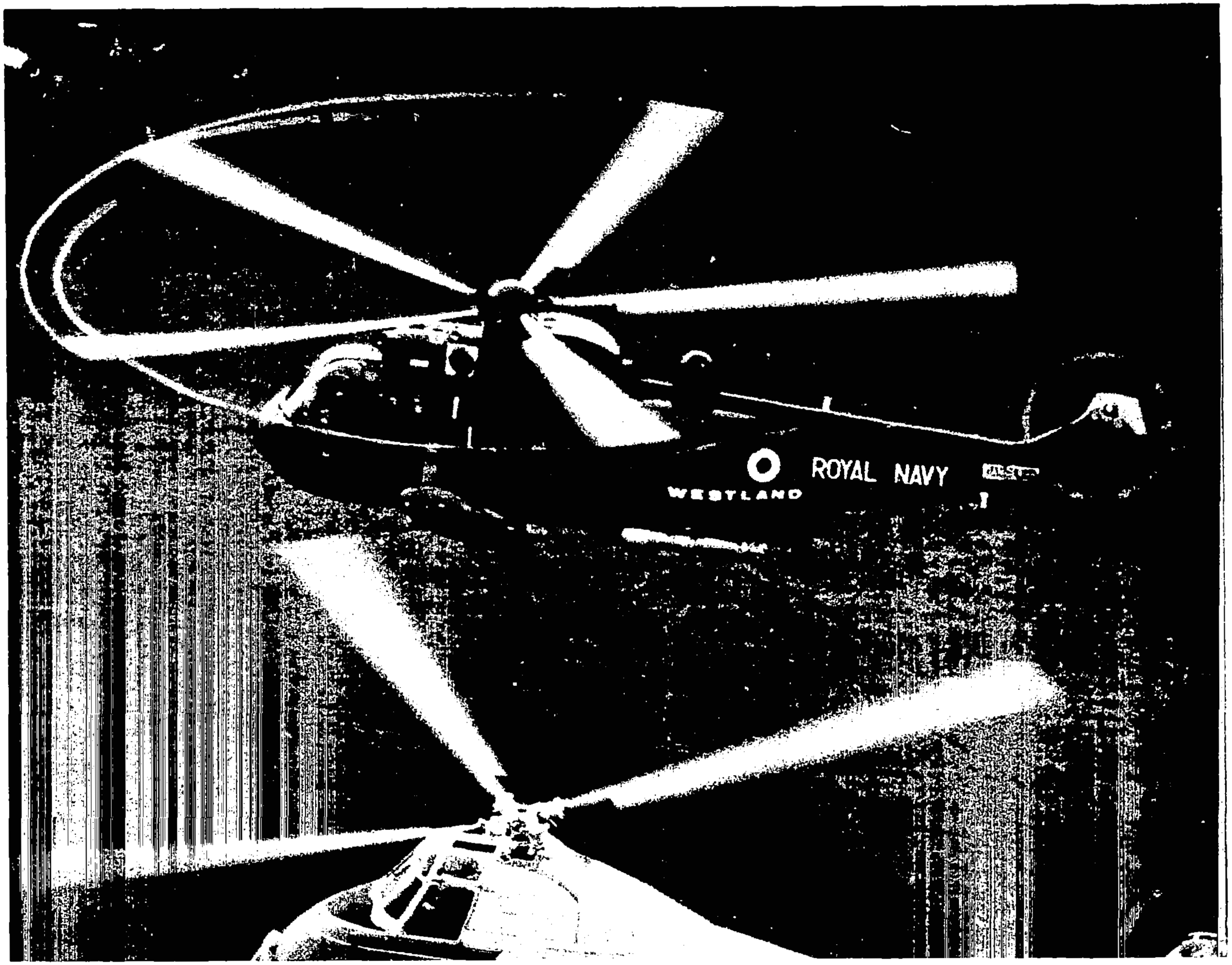


Plate 2. Photograph of hovering Sea King showing tip vortices.

HELICOPTER BLADE SLAP ~ NARROW-BAND ANALYSIS

FIG. 1

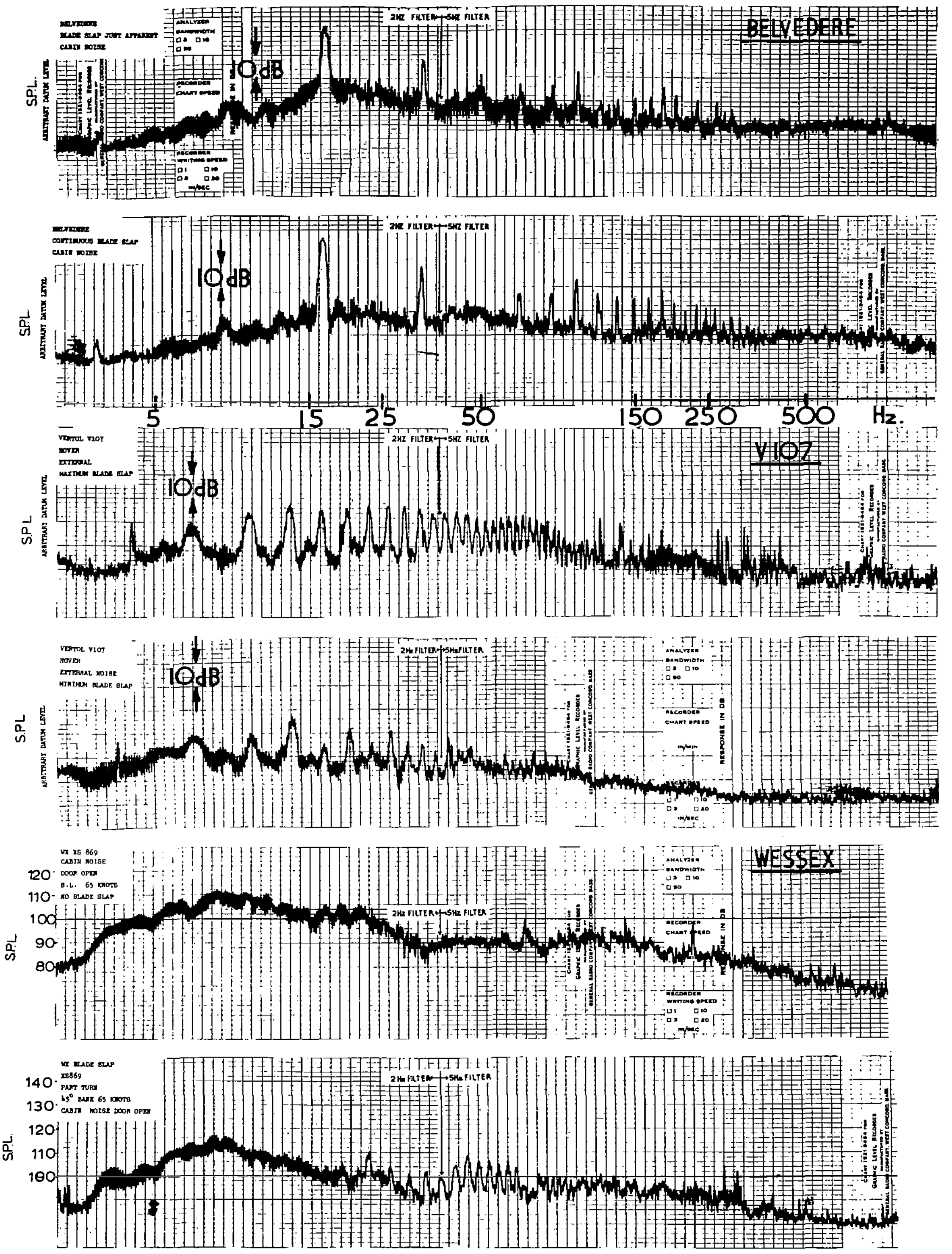
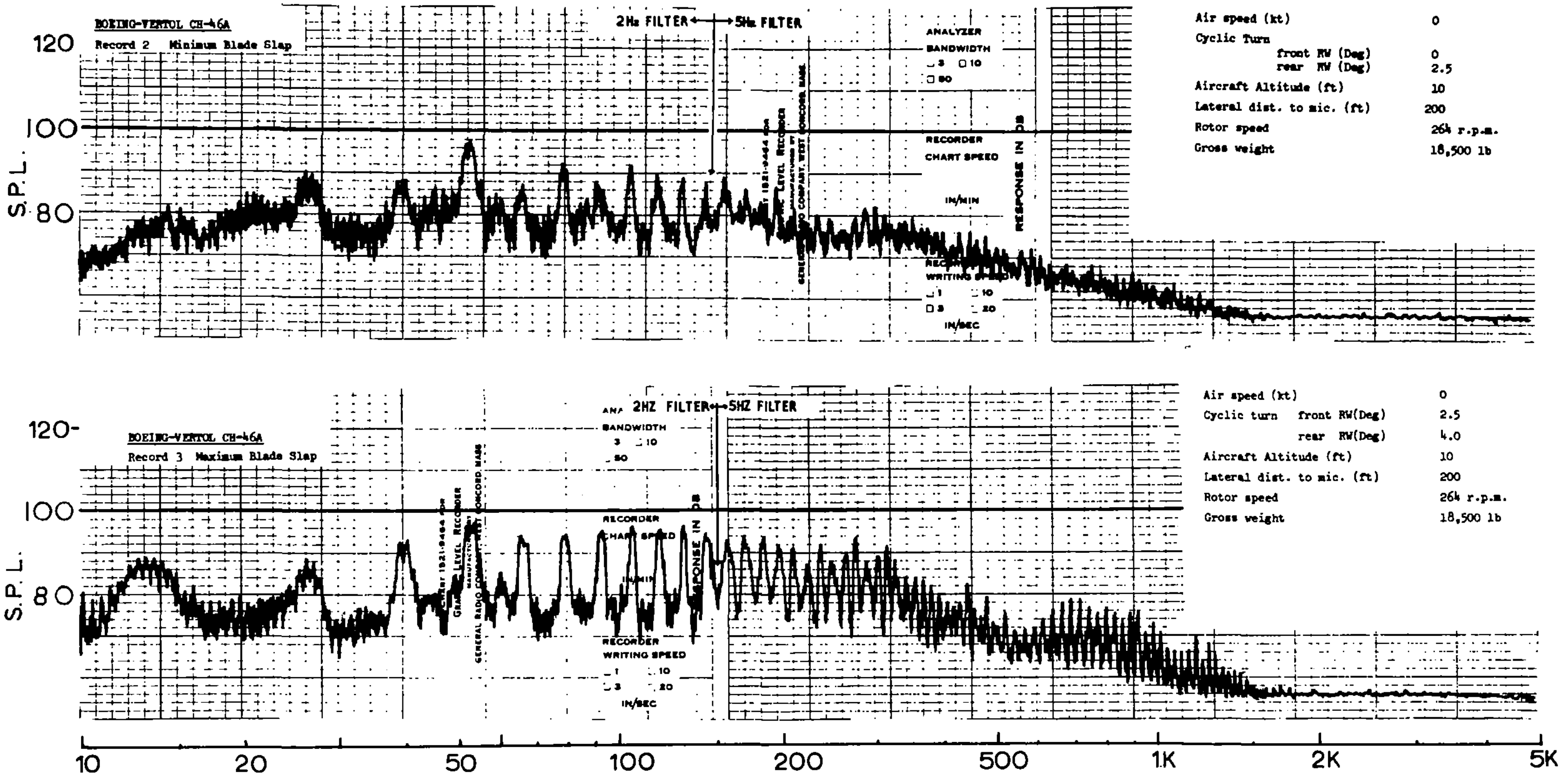


Fig 1.

HELICOPTER BLADE SLAP ~ NARROW-BAND ANALYSIS~CH-46A

FIG.2A



Air speed (kt)	0
Cyclic Turn front RW (Deg)	0
rear RW (Deg)	2.5
Aircraft Altitude (ft)	10
Lateral dist. to mic. (ft)	200
Rotor speed	264 r.p.m.
Gross weight	18,500 lb

Air speed (kt)	0
Cyclic turn front RW(Deg)	2.5
rear RW(Deg)	4.0
Aircraft Altitude (ft)	10
Lateral dist. to mic. (ft)	200
Rotor speed	264 r.p.m.
Gross weight	18,500 lb

FIG.2A

HELICOPTER BLADE SLAP ~ NARROW-BAND ANALYSIS FIG. 2B

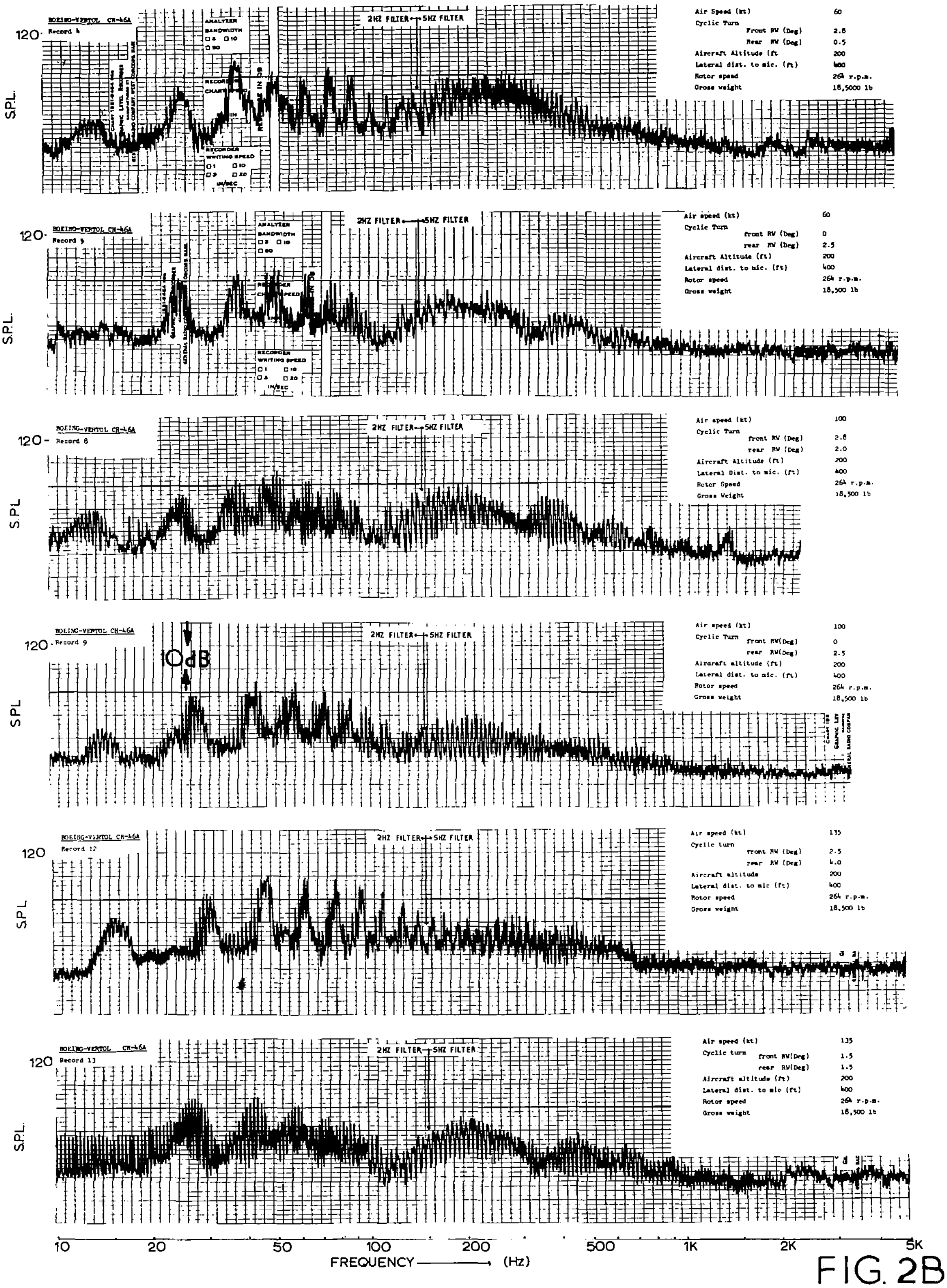


FIG. 2B

HELICOPTER BLADE SLAP~ NARROW-BAND ANALYSIS

FIG. 3

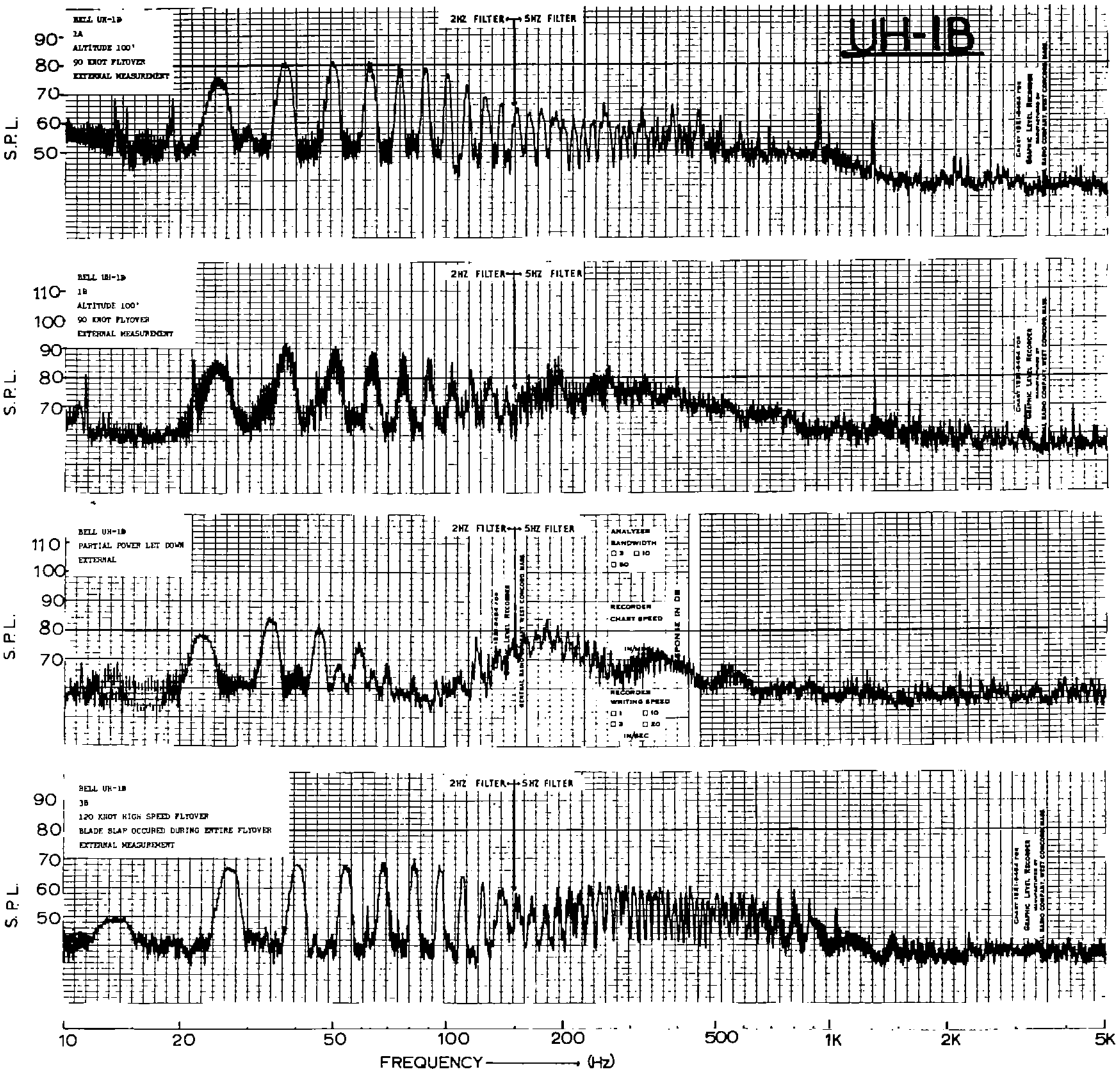


FIG. 3

OSCILLOGRAMS OF HELICOPTER NOISE

WESSEX-MK 5
70-80KNOTS: 50° BANK - WITH BLADE SLAP

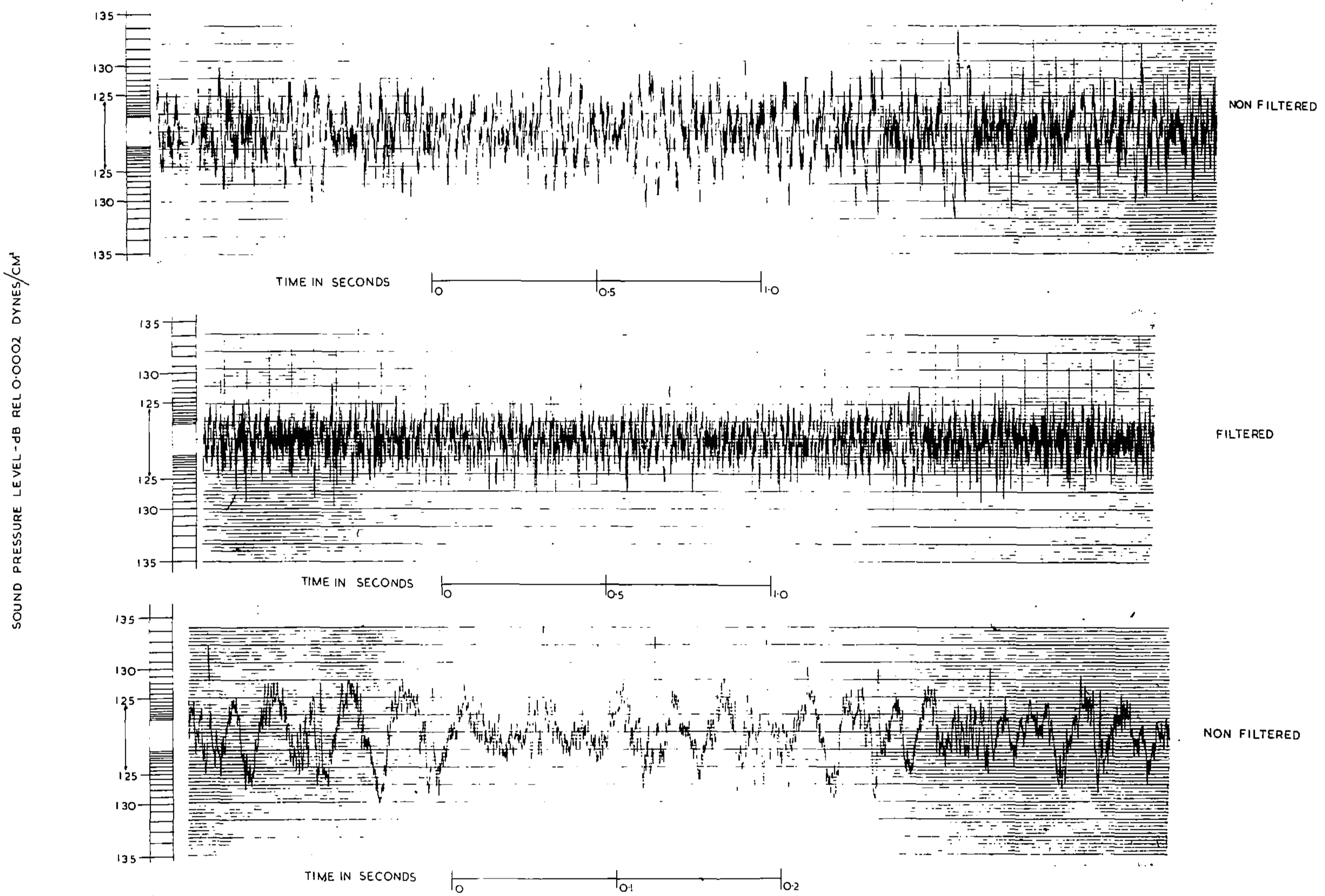


FIG. 4a

OSCILLOGRAMS OF HELICOPTER NOISE

WESSEX-MK 5
CABIN NOISE-NO BLADE SLAP

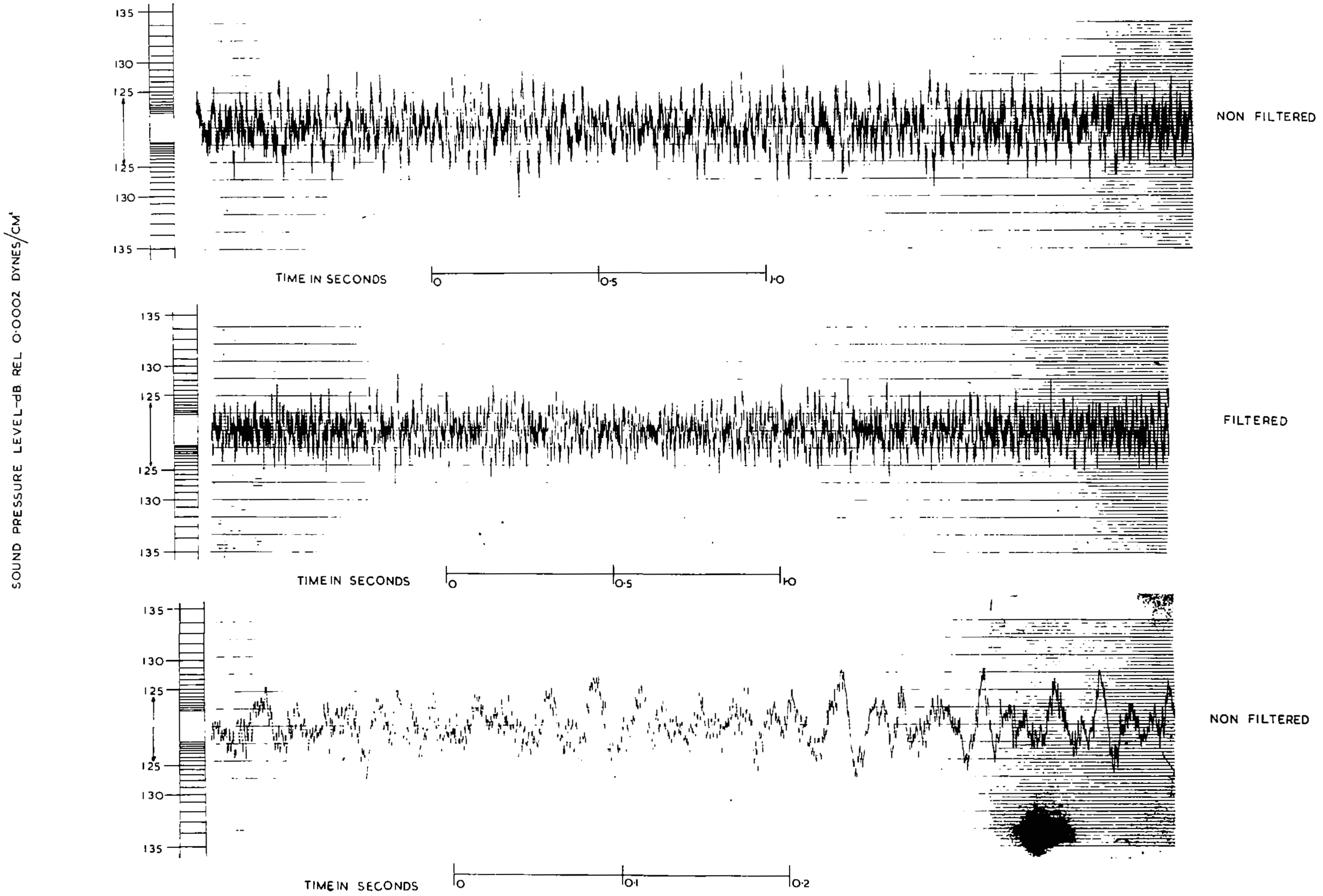


FIG 4b

OSCILLOGRAMS OF HELICOPTER NOISE SYCAMORE 80 KNOTS- PORT TURN 40°-50°

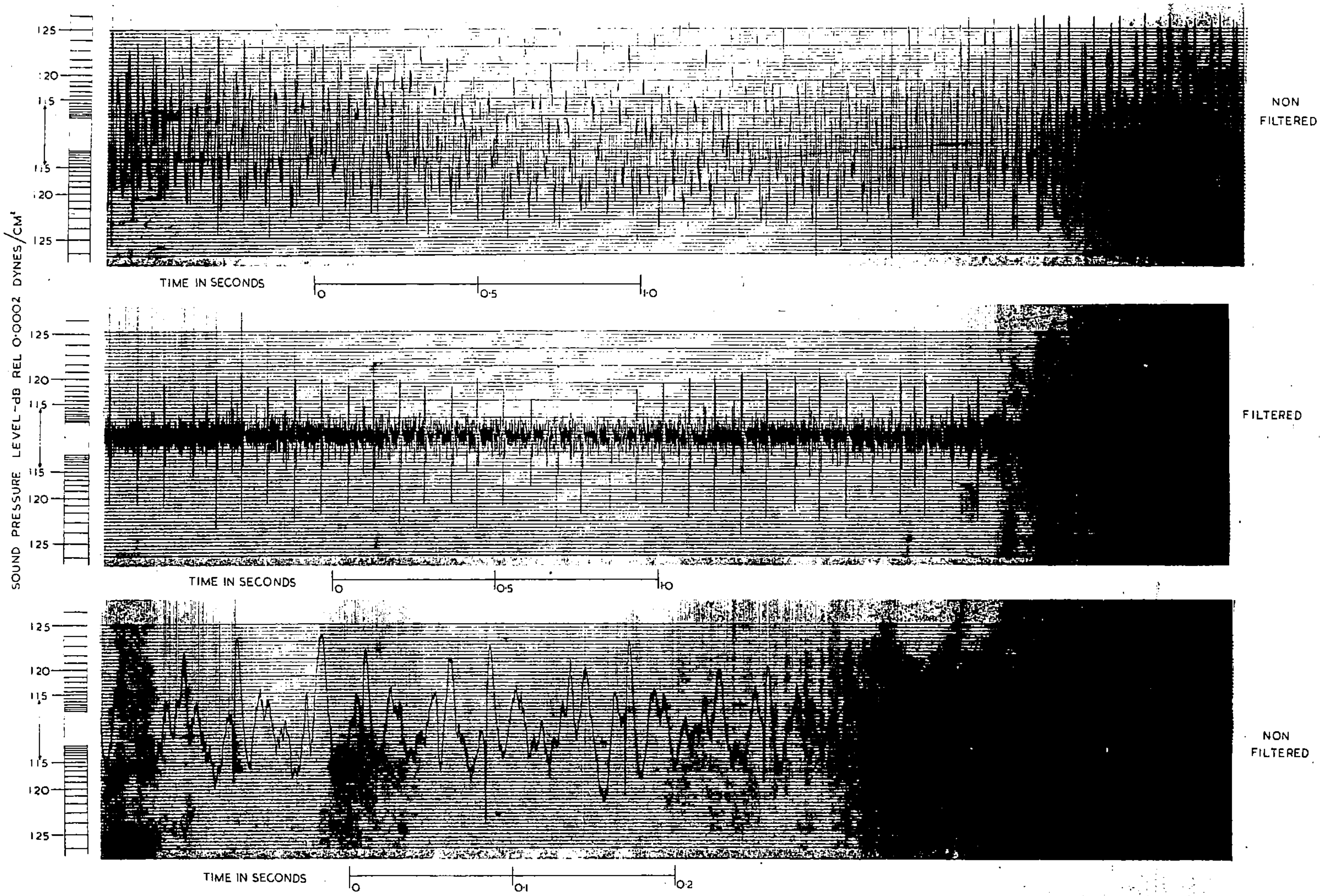


FIG.5a

OSCILLOGRAMS OF HELICOPTER NOISE

SYCAMORE

STRAIGHT AND LEVEL- 80 KNOTS

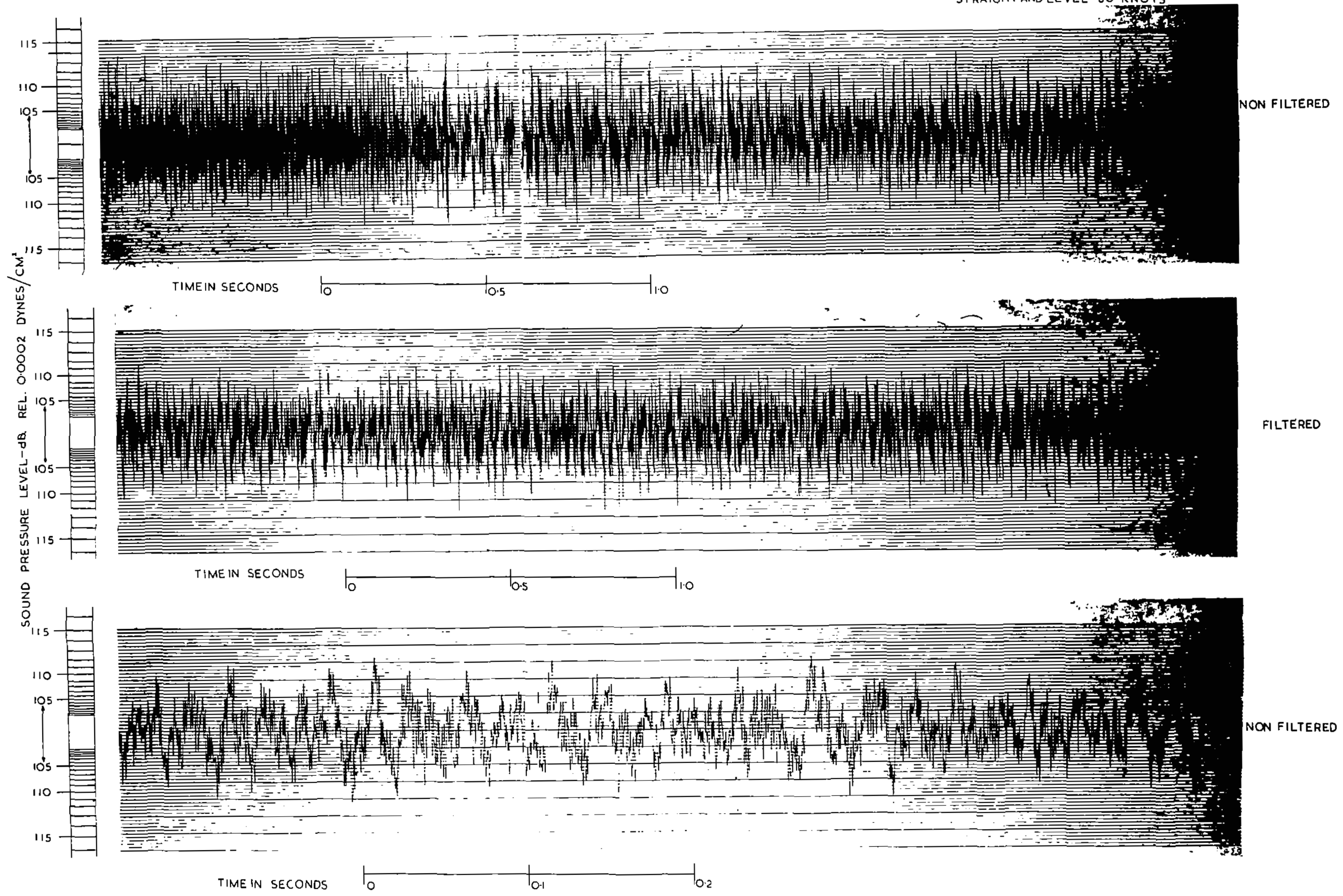


FIG. 5b

OSCILLOGRAMS OF HELICOPTER NOISE

BELL-UH 1B
INSIDE CABIN-PARTIAL POWER DECENT, WITH BLADE SLAP

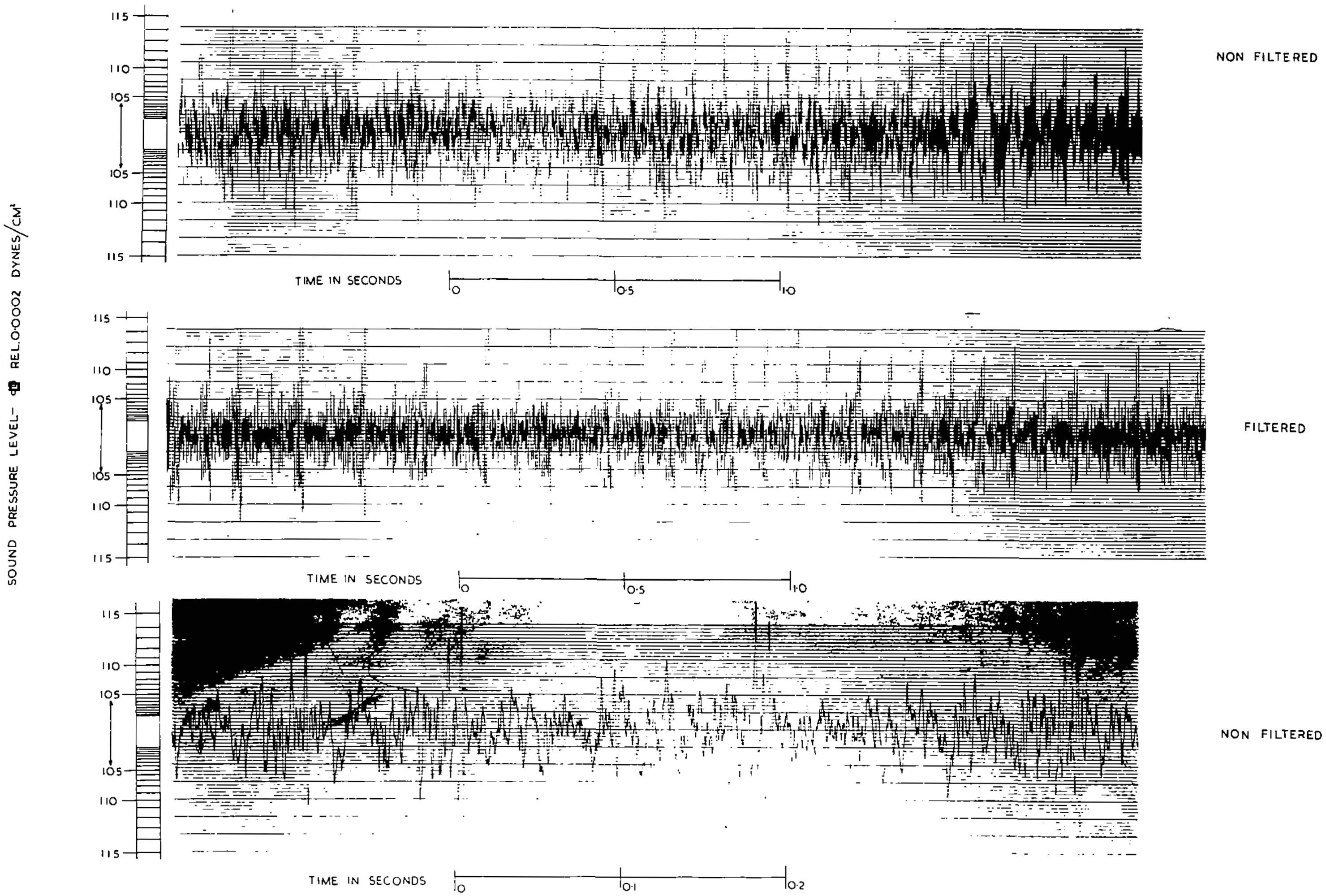


FIG. 6a

OSCILLOGRAMS OF HELICOPTER NOISE

BELL-UH 1B

INSIDE CABIN-90 KNOTS-NO BLADE SLAP

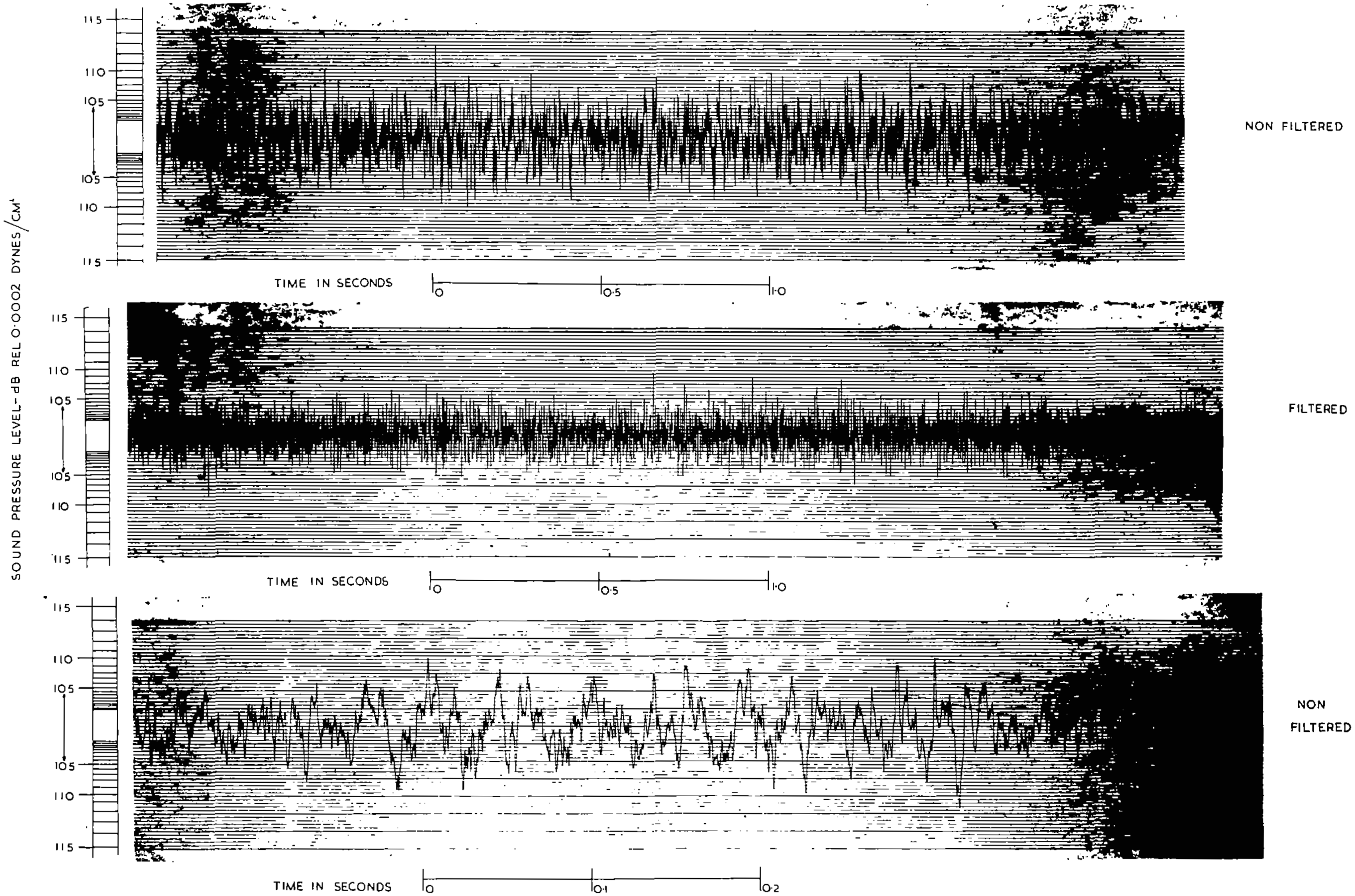
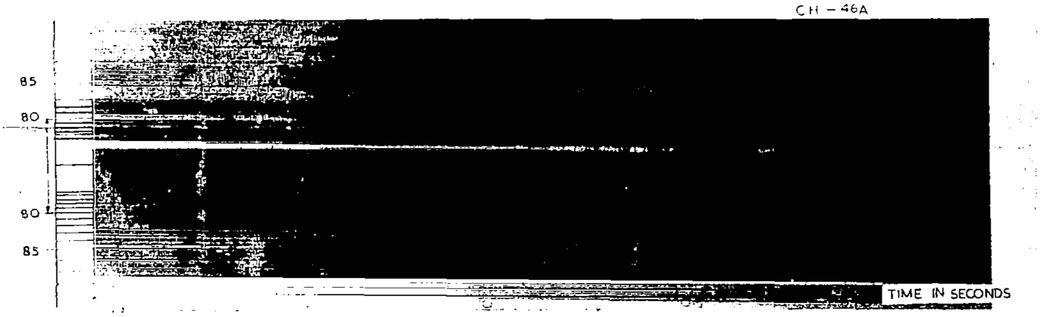


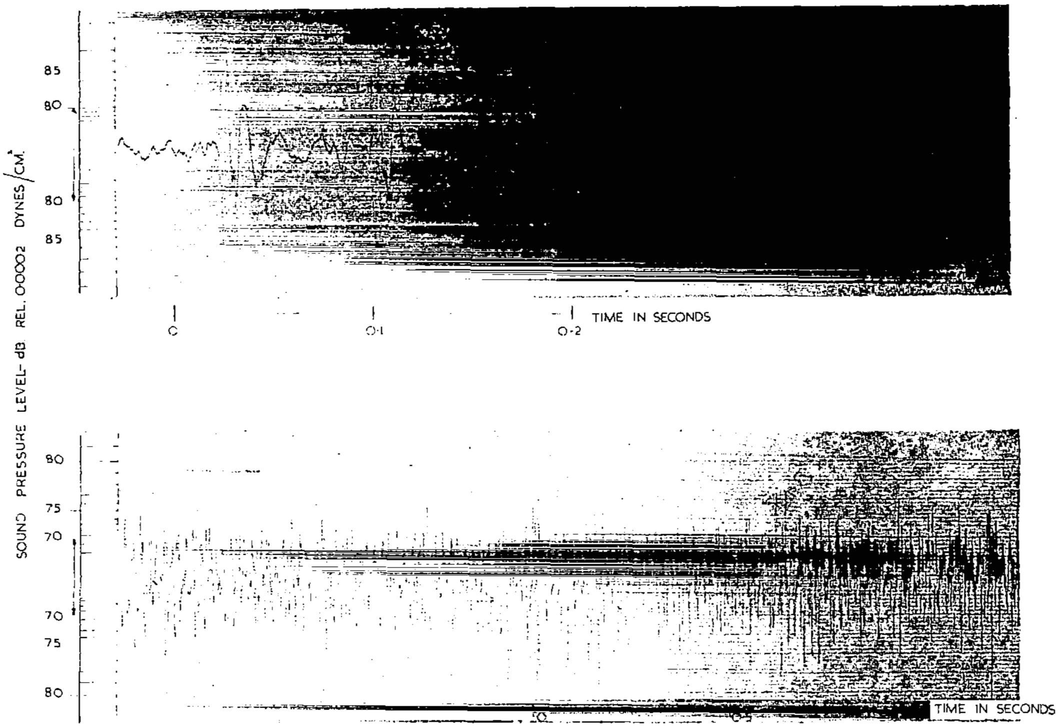
FIG.6b

OSCILLOGRAMS OF HELICOPTER NOISE

CH – 46A



HOVER – 10' ALT.– 200' DIST.– CYCLIC TRIM(2·5 FWD,1·0 AFT)



HOVER – 10' ALT. – 200' DIST. – CYCLIC TRIM (0,2·5 AFT)

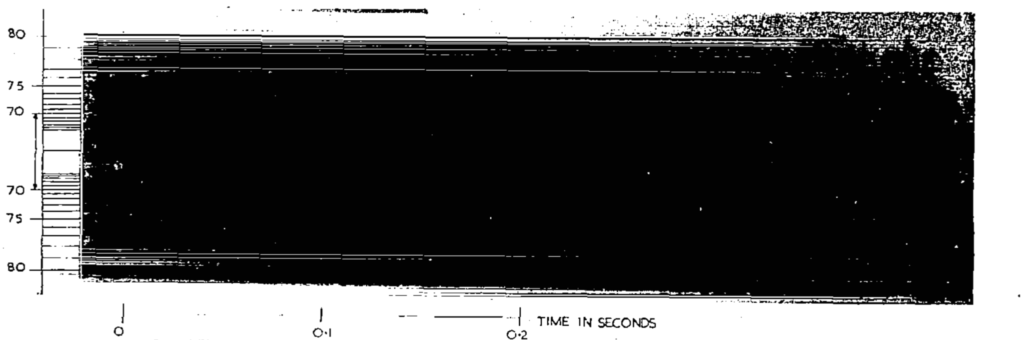
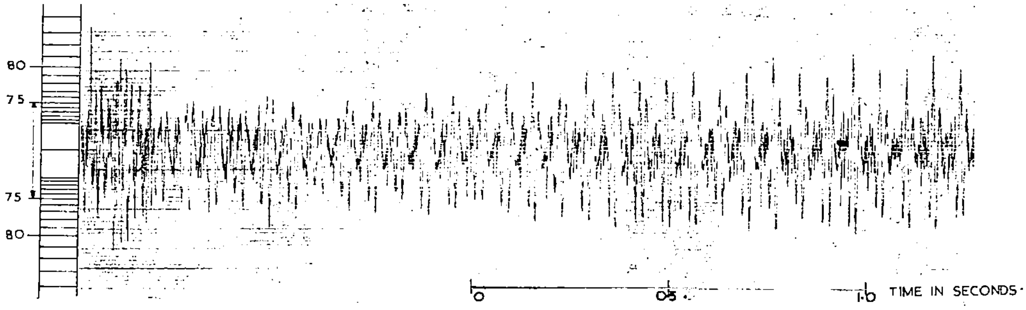


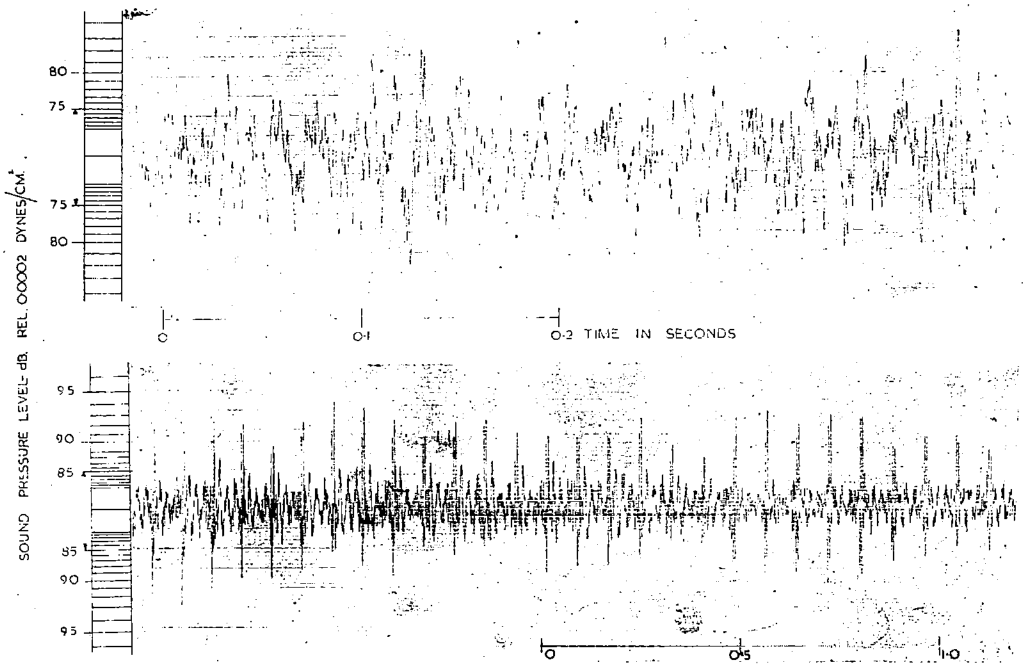
FIG. 7

OSCILLOGRAMS OF HELICOPTER NOISE

CH - 46A



100 KNOTS – 200' ALT. – 400' DIST. – CYCLIC TRIM (0, 2.5 AFT)



100 KNOTS – 200' ALT. – 400' DIST. – CYCLIC TRIM (2.8 FWD., 2.0 FWD.)

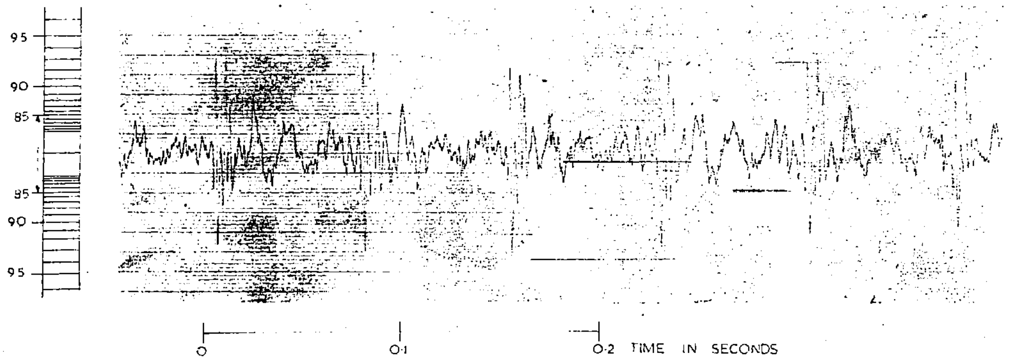


FIG.8

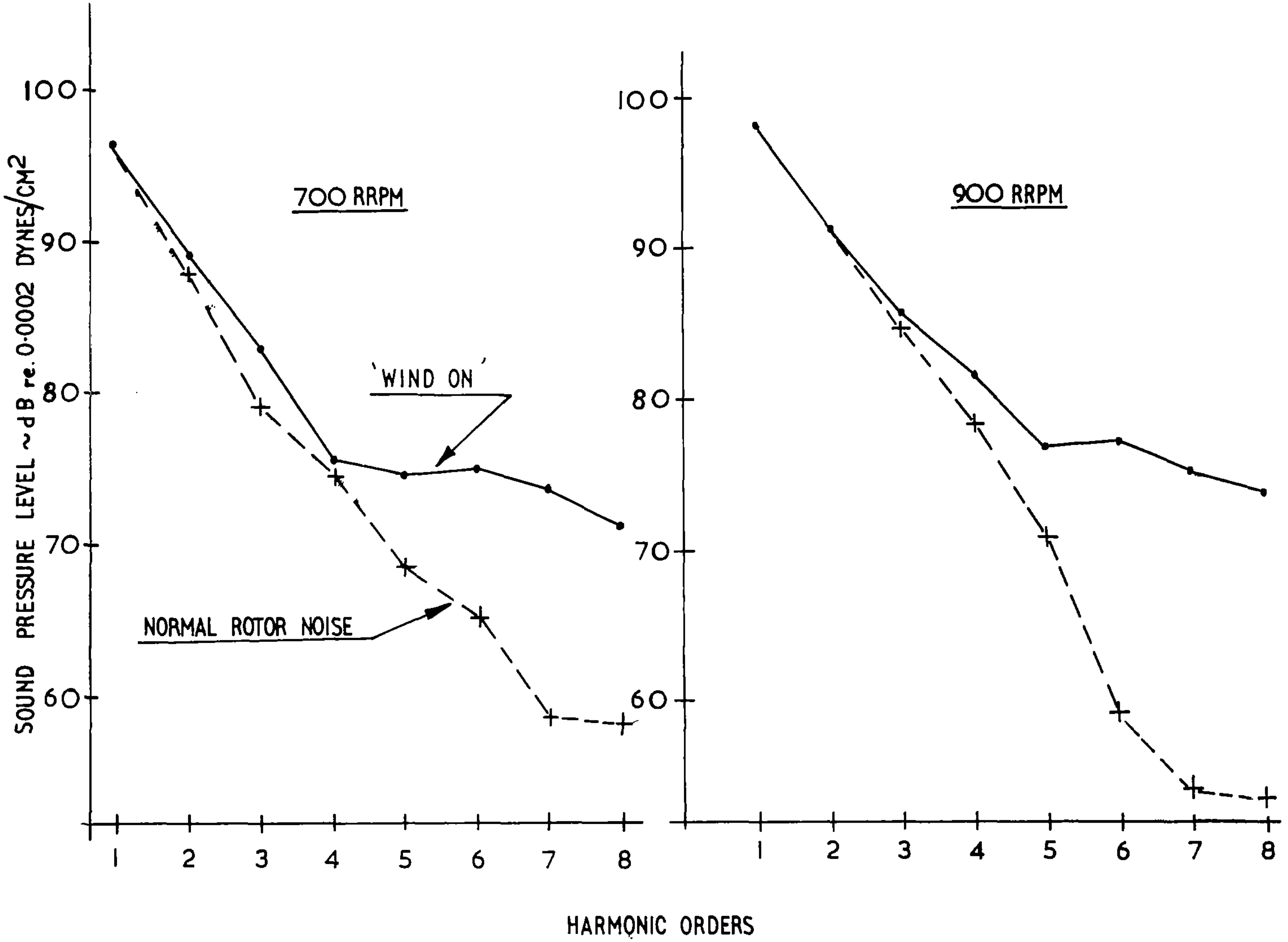


FIG.9 EFFECT OF 'WIND' ON DISCRETE ROTOR NOISE.

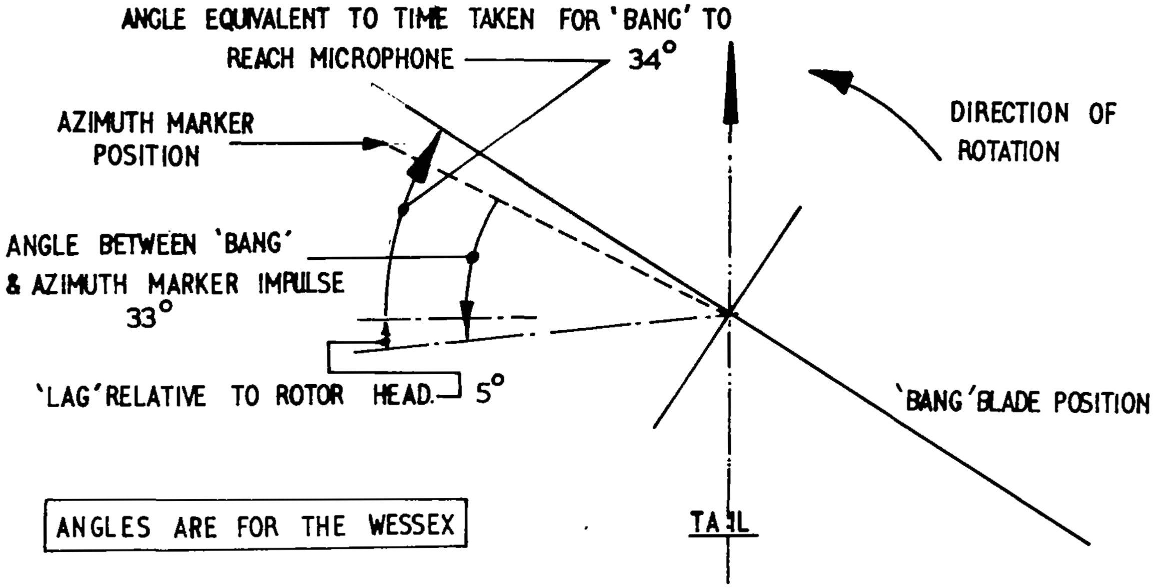


FIG. 10. BLADE 'BANG' AZIMUTH LOCATION

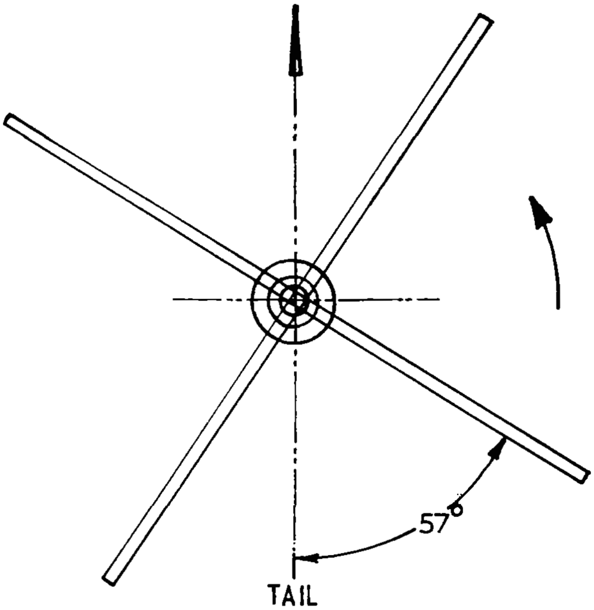


FIG. 11(a) 'WESSEX' RESULT.

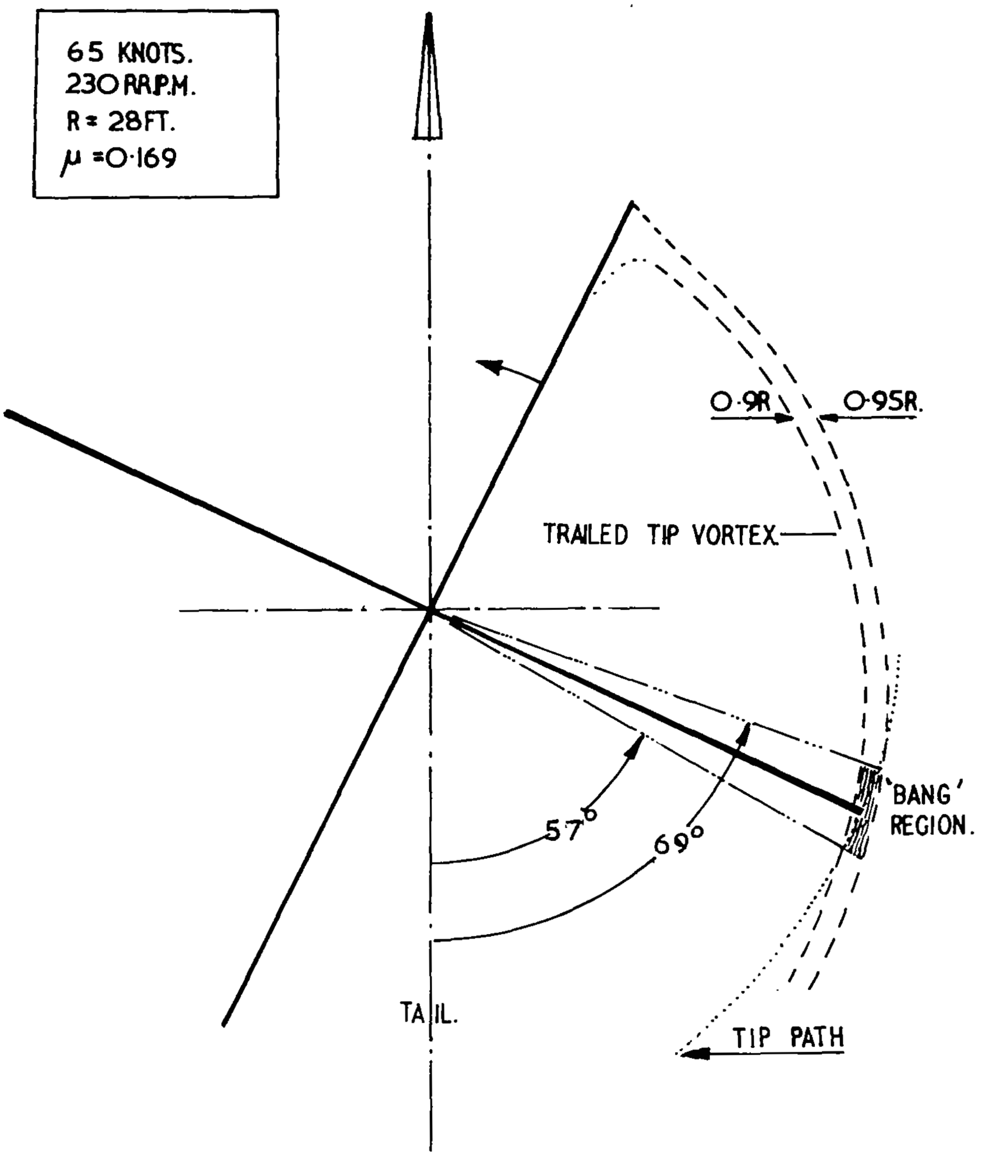


FIG.11(b). RIGID WAKE MODEL FOR WESSEX.

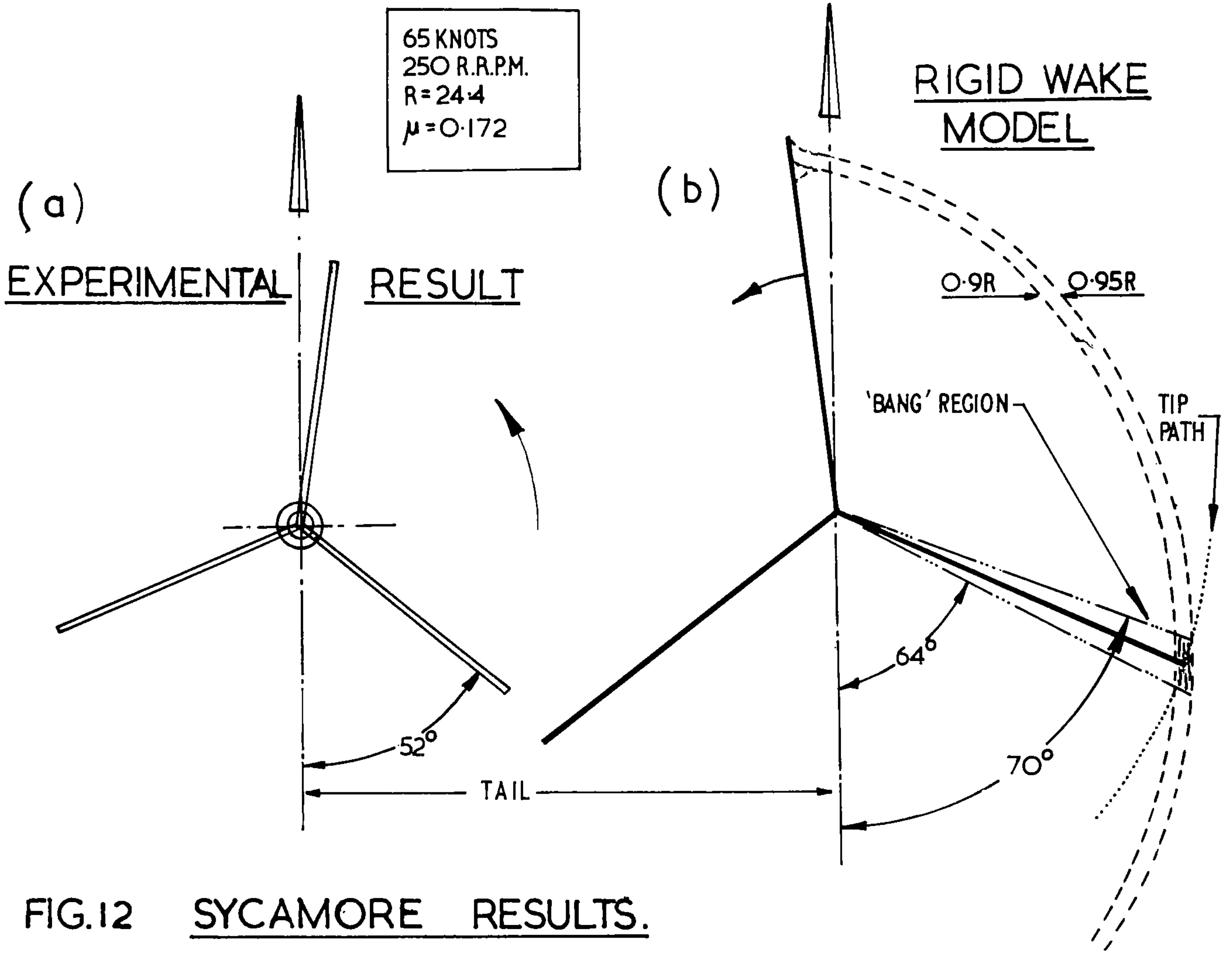
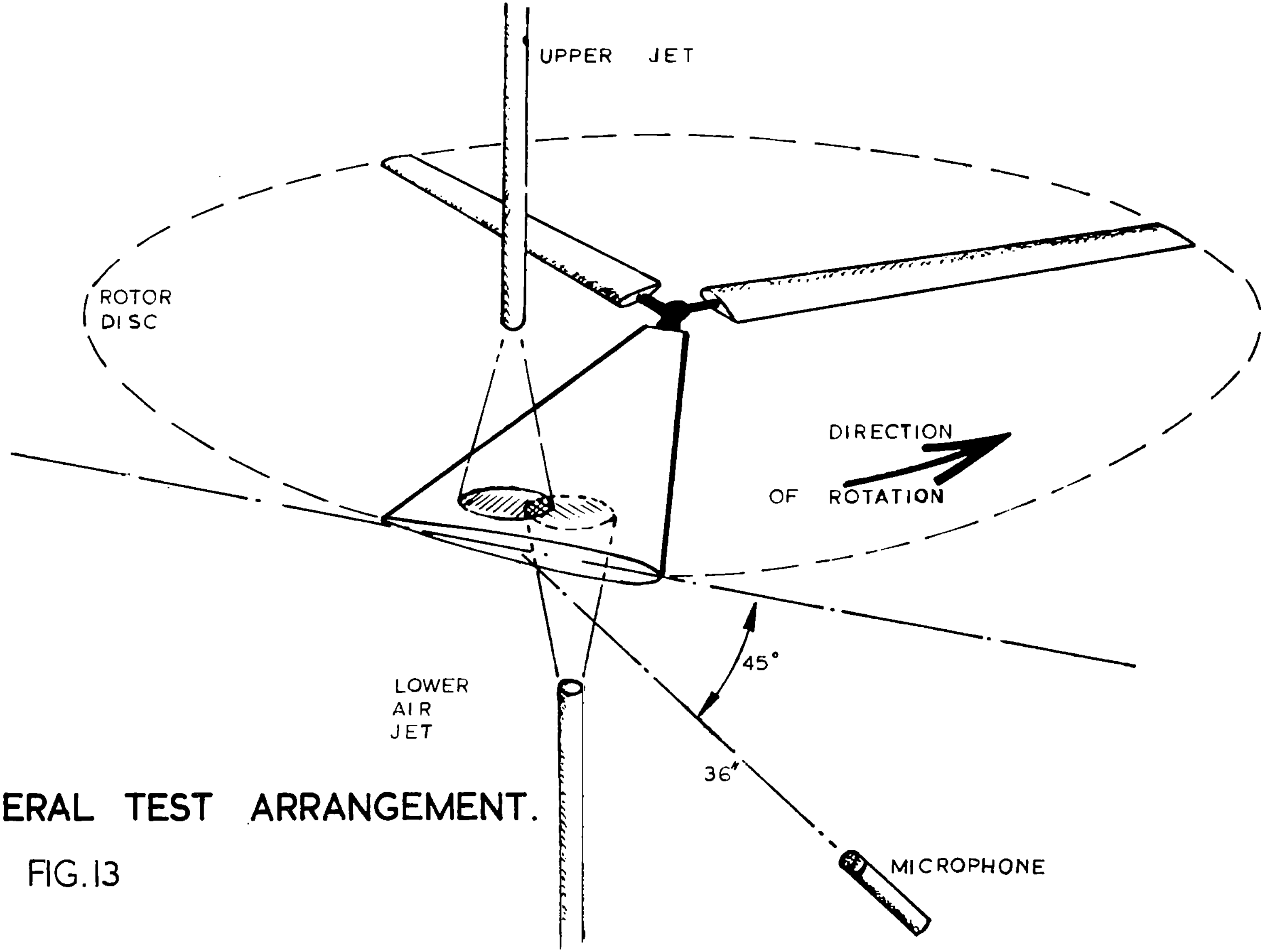


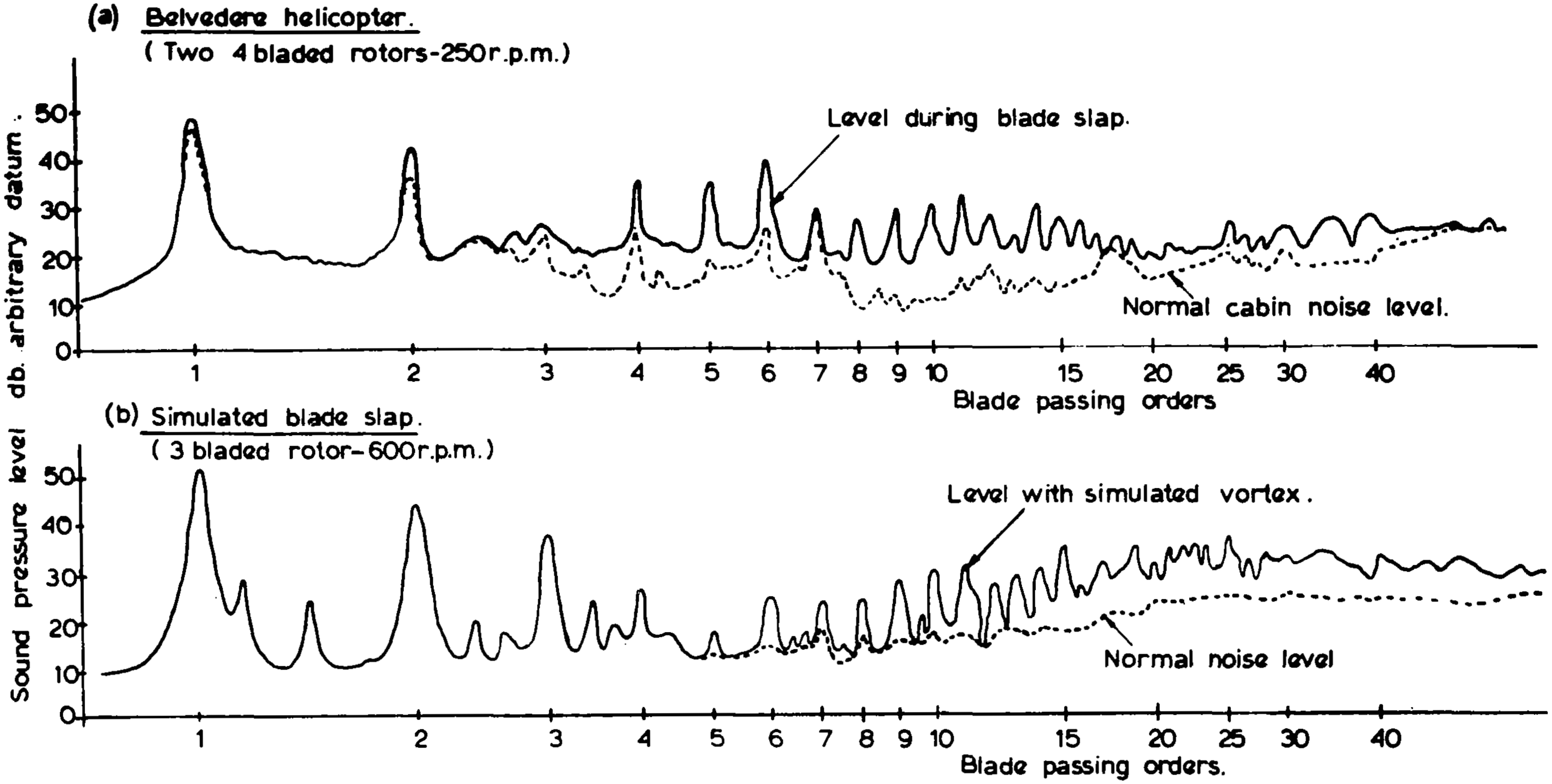
FIG.12 SYCAMORE RESULTS.



GENERAL TEST ARRANGEMENT.

FIG. 13

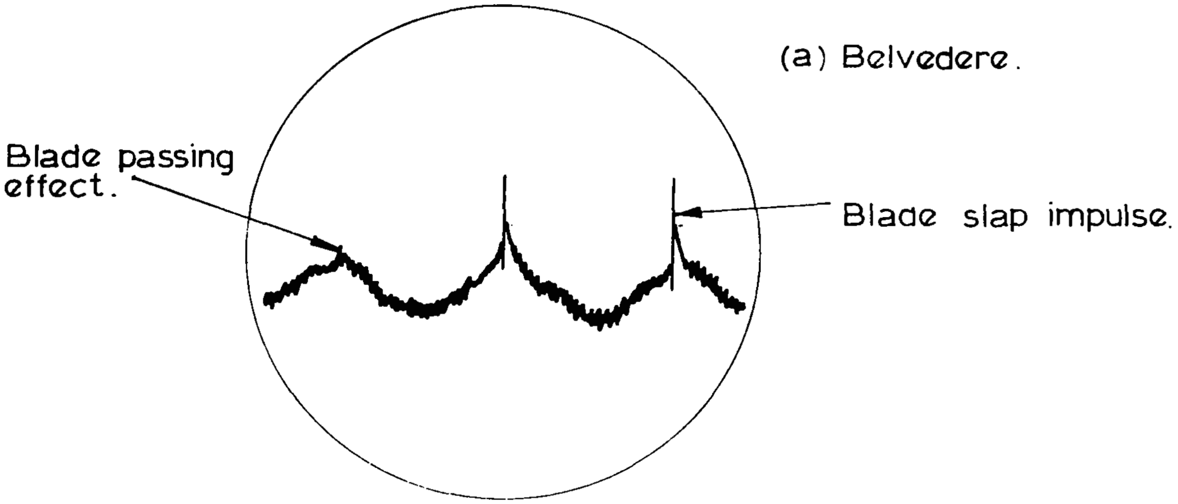
NARROW BAND ANALYSIS - (1·5%)



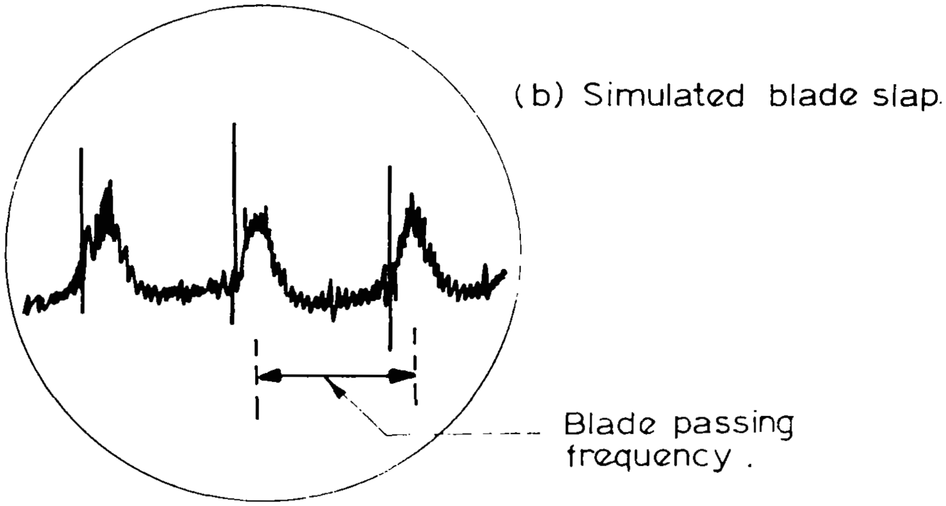
(a) Belvedere helicopter.
(Two 4 bladed rotors-250 r.p.m.)

(b) Simulated blade slap.
(3 bladed rotor-600 r.p.m.)

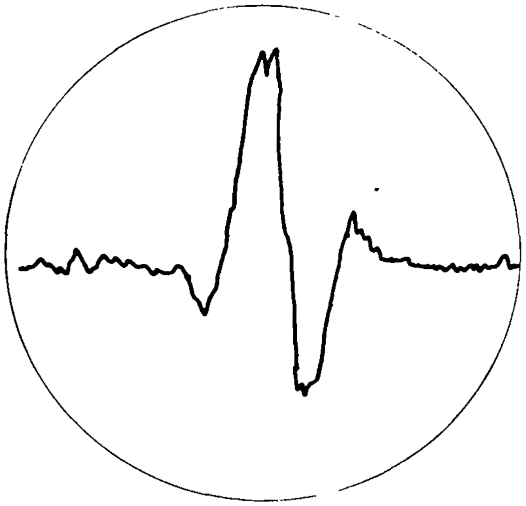
FIG. 14 COMPARISON OF HELICOPTER AND SIMULATED BLADE SLAP



(a) Belvedere.



(b) Simulated blade slap.



(c) Blade slap impulse

Configuration I
600 r.p.m.

FIG. 15 Oscillograms

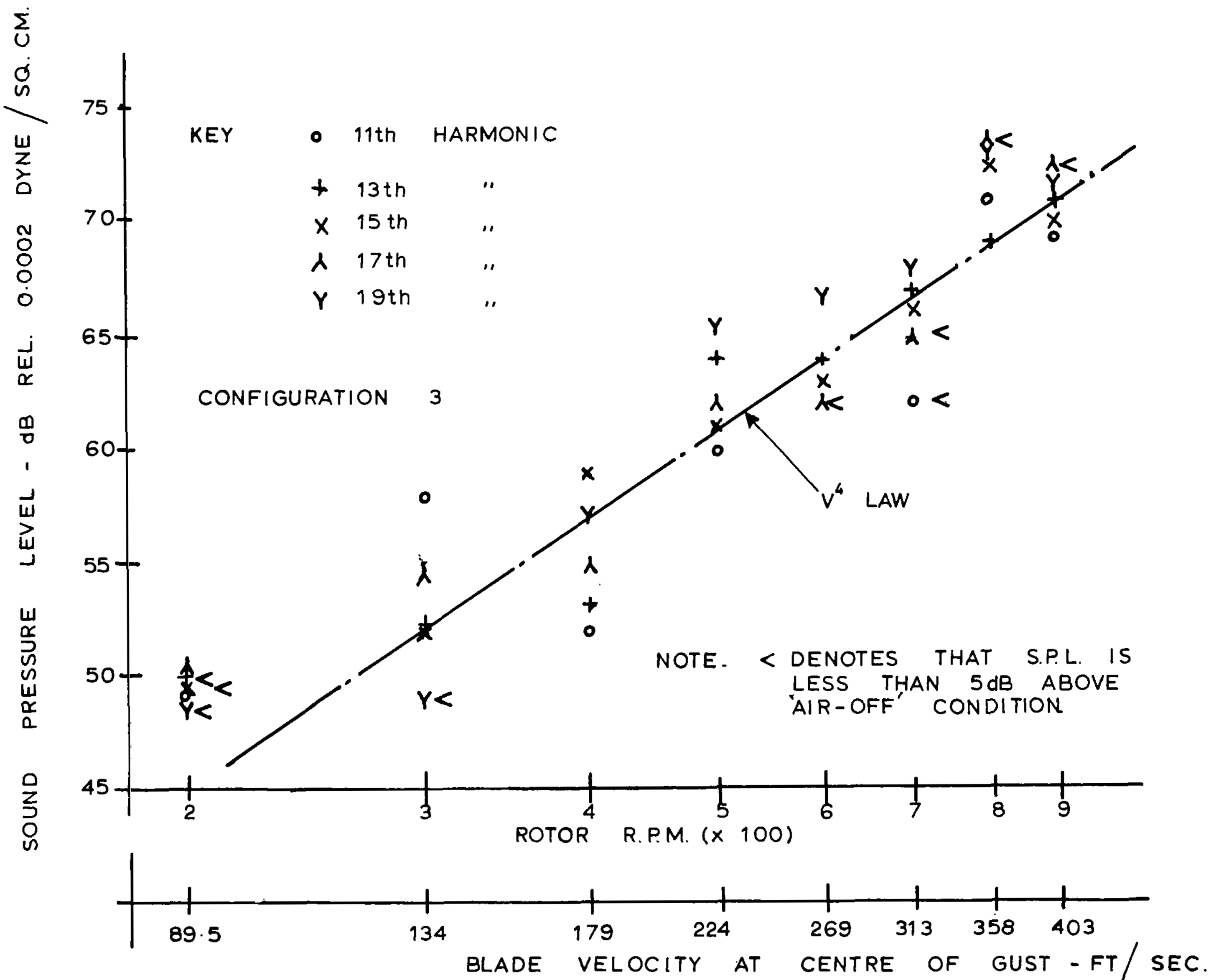


Figure 16 Variation of sound pressure level with rotor speed.

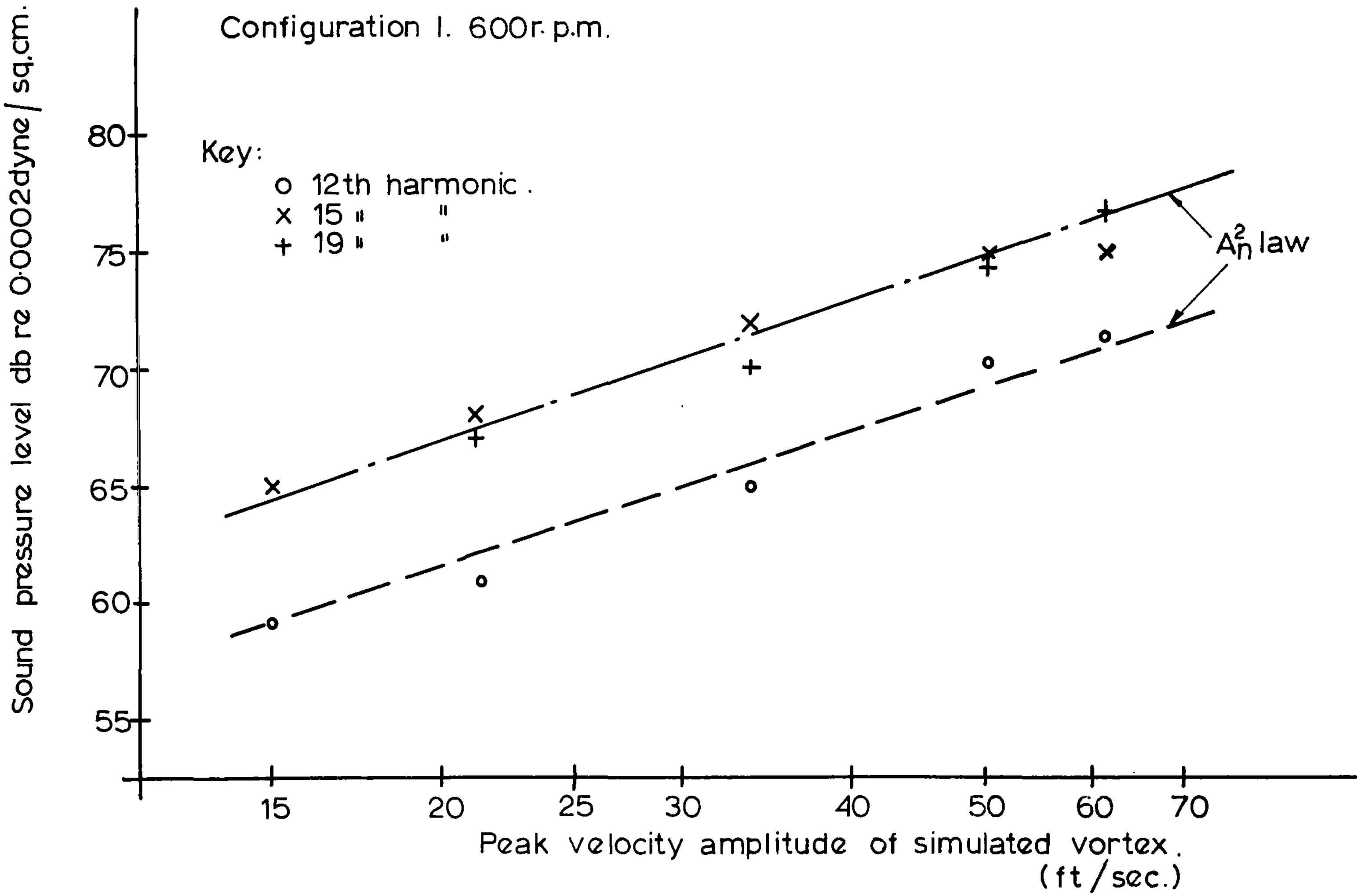


Figure 17. Variation of sound pressure levels with amplitude of simulated vortex.

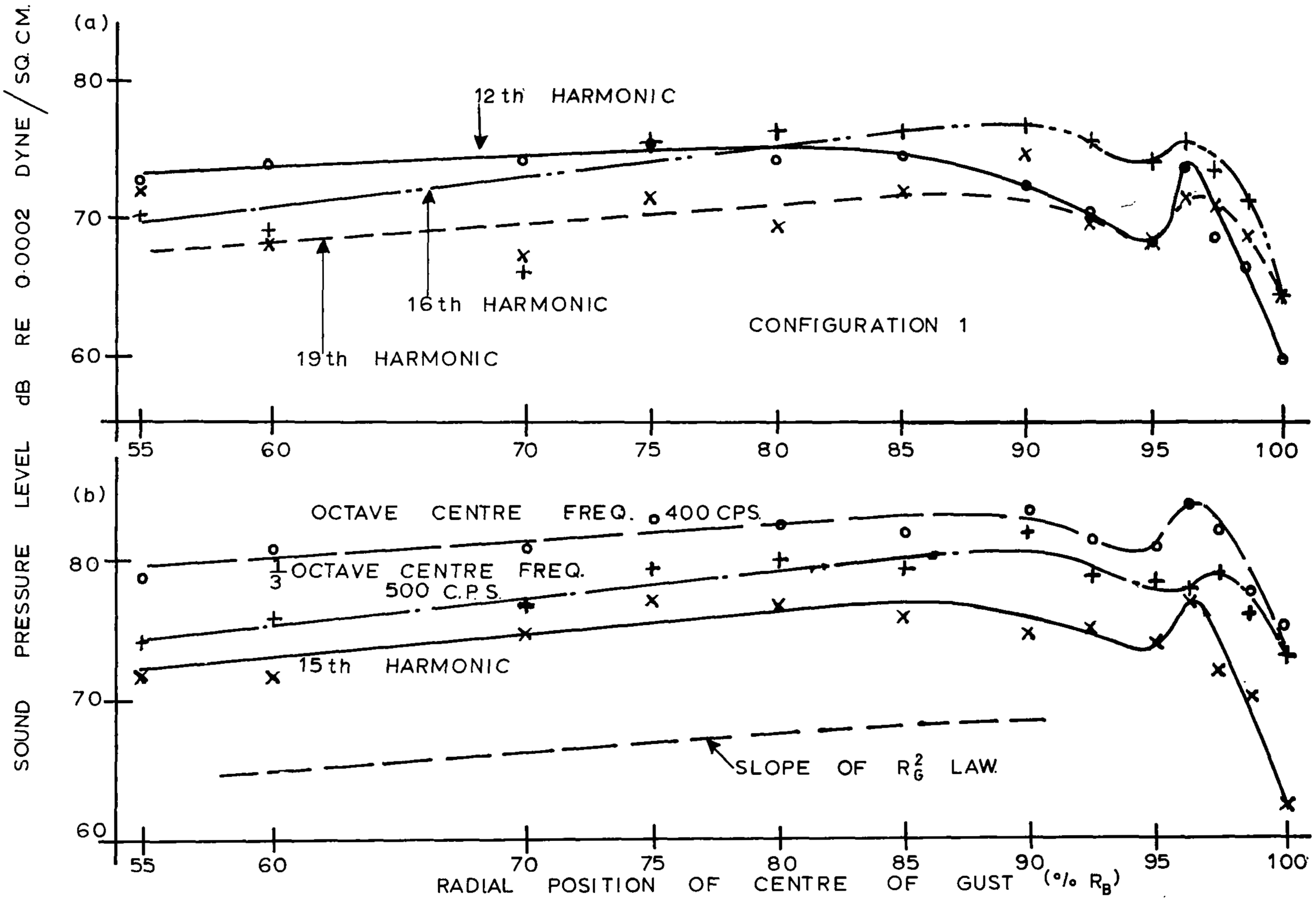


Figure 18. Variation of sound pressure levels with position of gust.

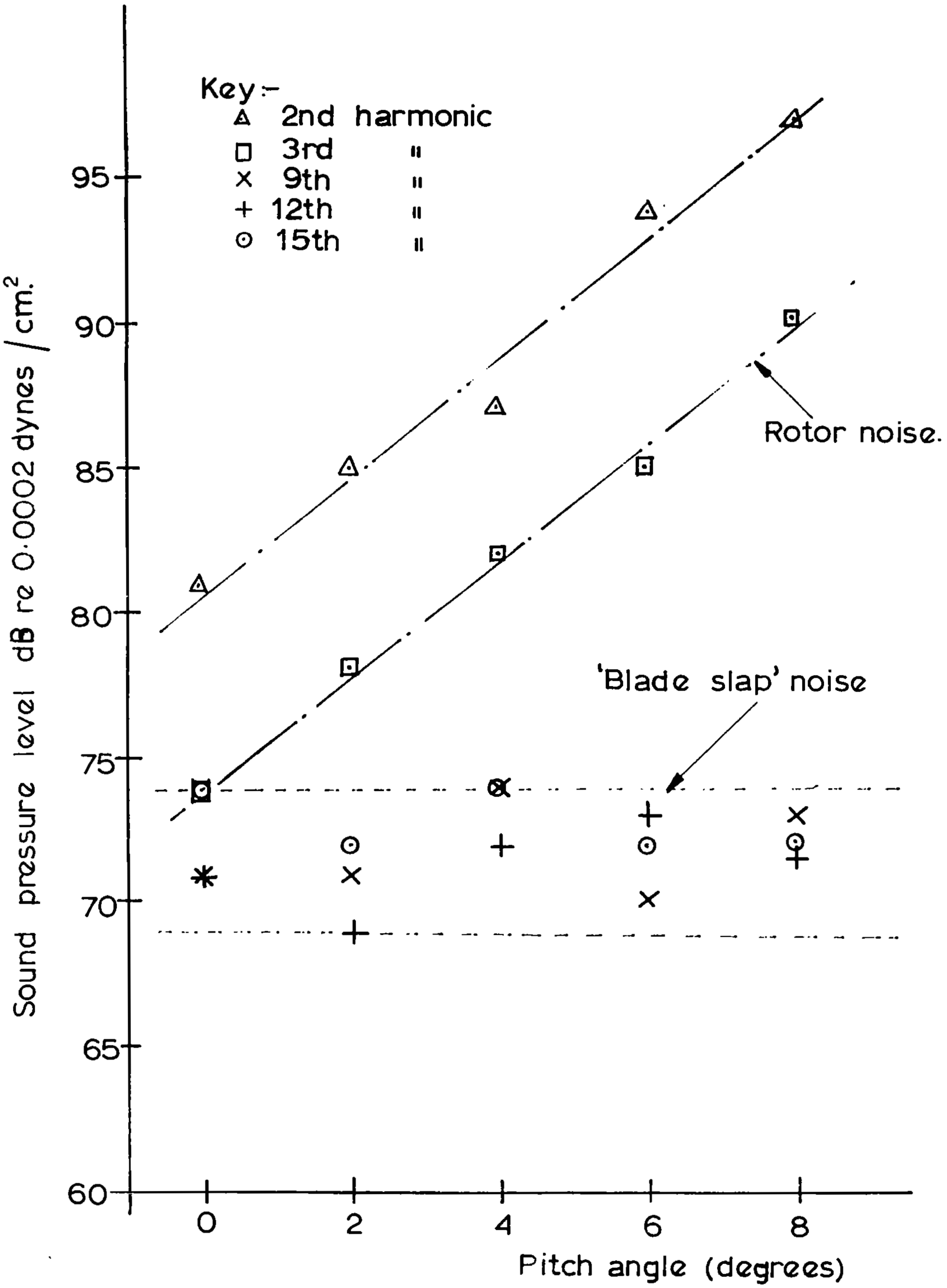


Figure 19 Variation of sound pressure levels with pitch of blade For configuration 1 (0·95R - 6000r.p.m.)

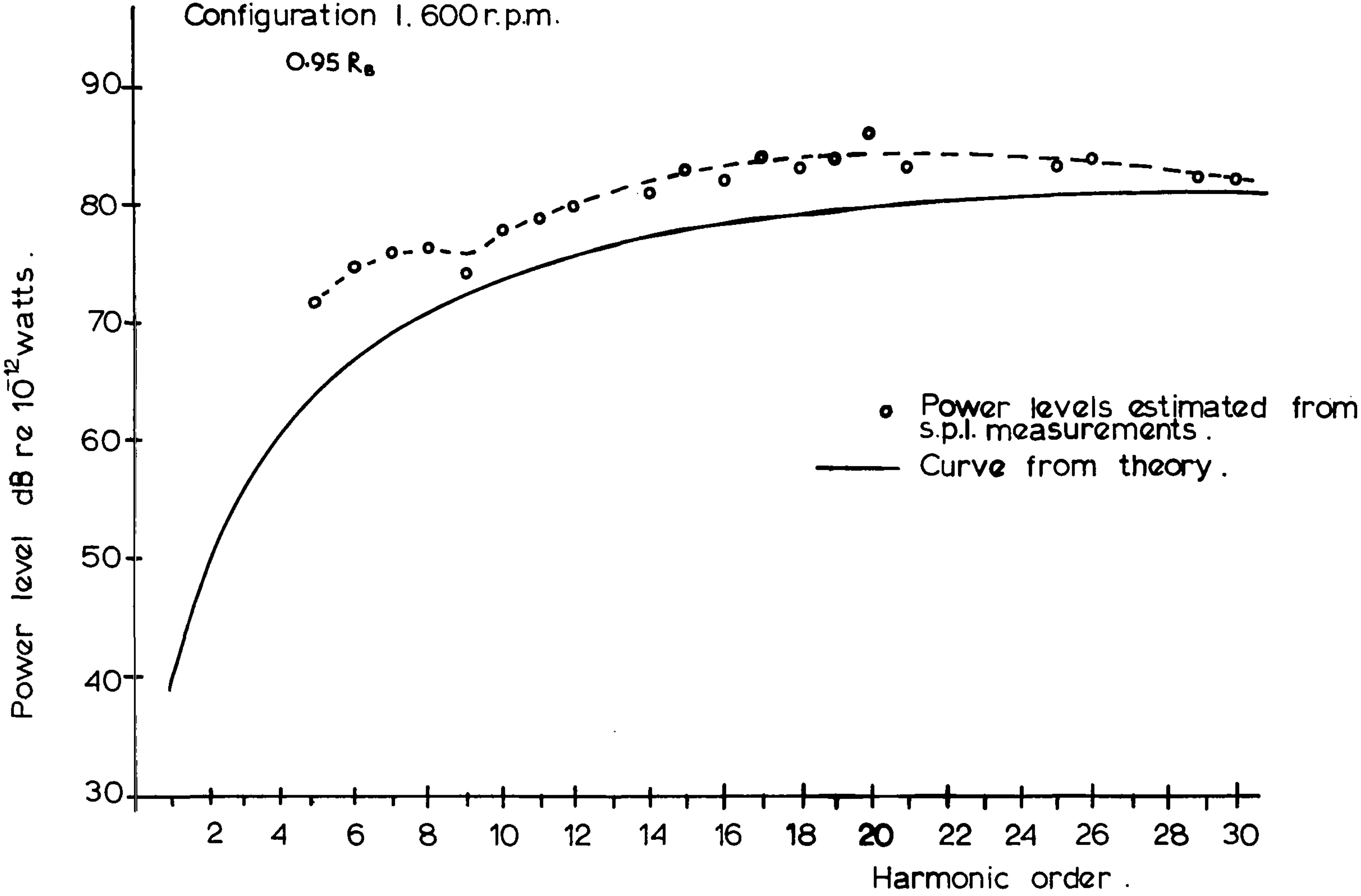
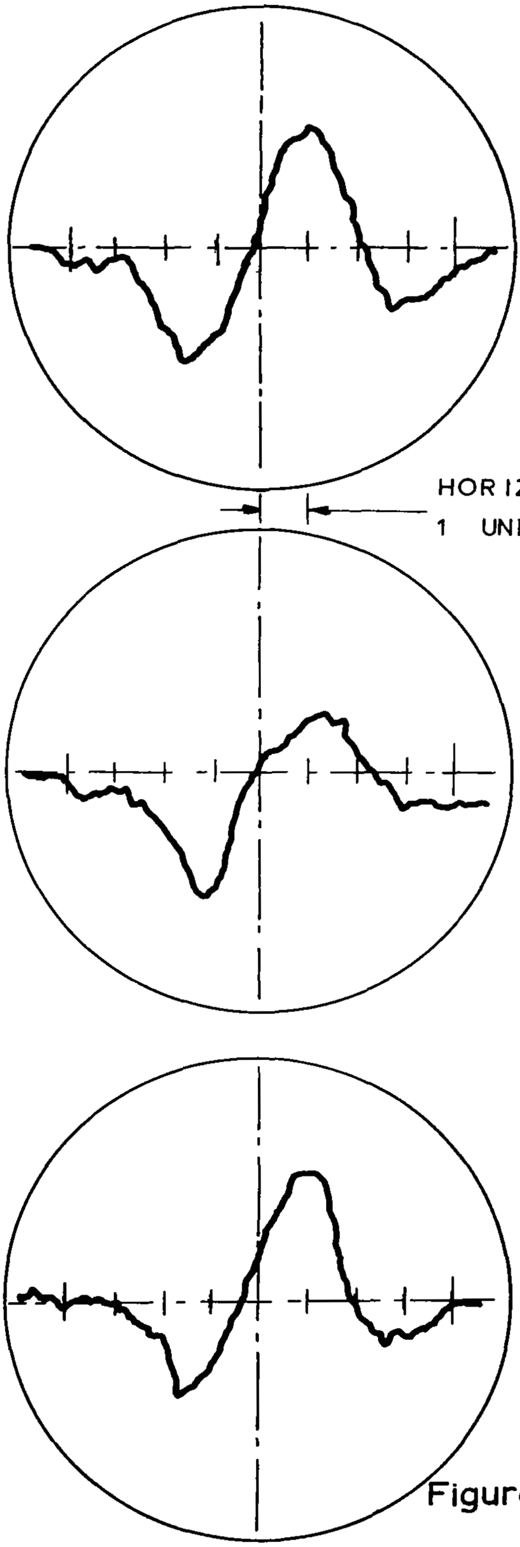


Figure 20 Comparison of calculated and estimated source power.



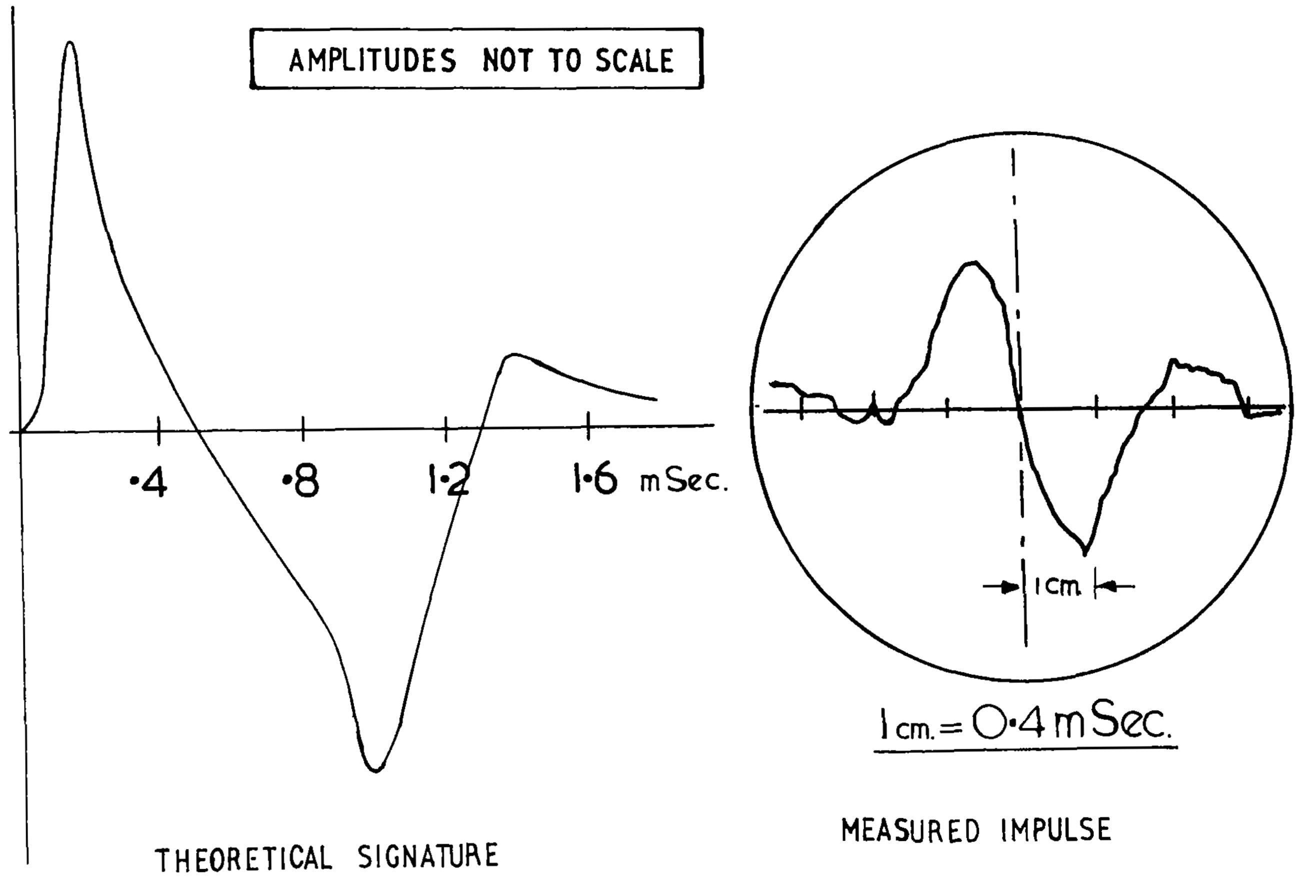
CONFIGURATION 3

470 R.P.M.
$0{\cdot}90\ R_B$

HORIZONTAL SCALE
1 UNIT ≡ 0·2 m. SEC.

OSCILLOGRAMS ILLUSTRATING THE VARIATION IN IMPULSE SHAPE.

Figure 21. Oscillogram.



THEORETICAL SIGNATURE

MEASURED IMPULSE

FIG. 22. Comparison of Theoretical and Measured Signature.

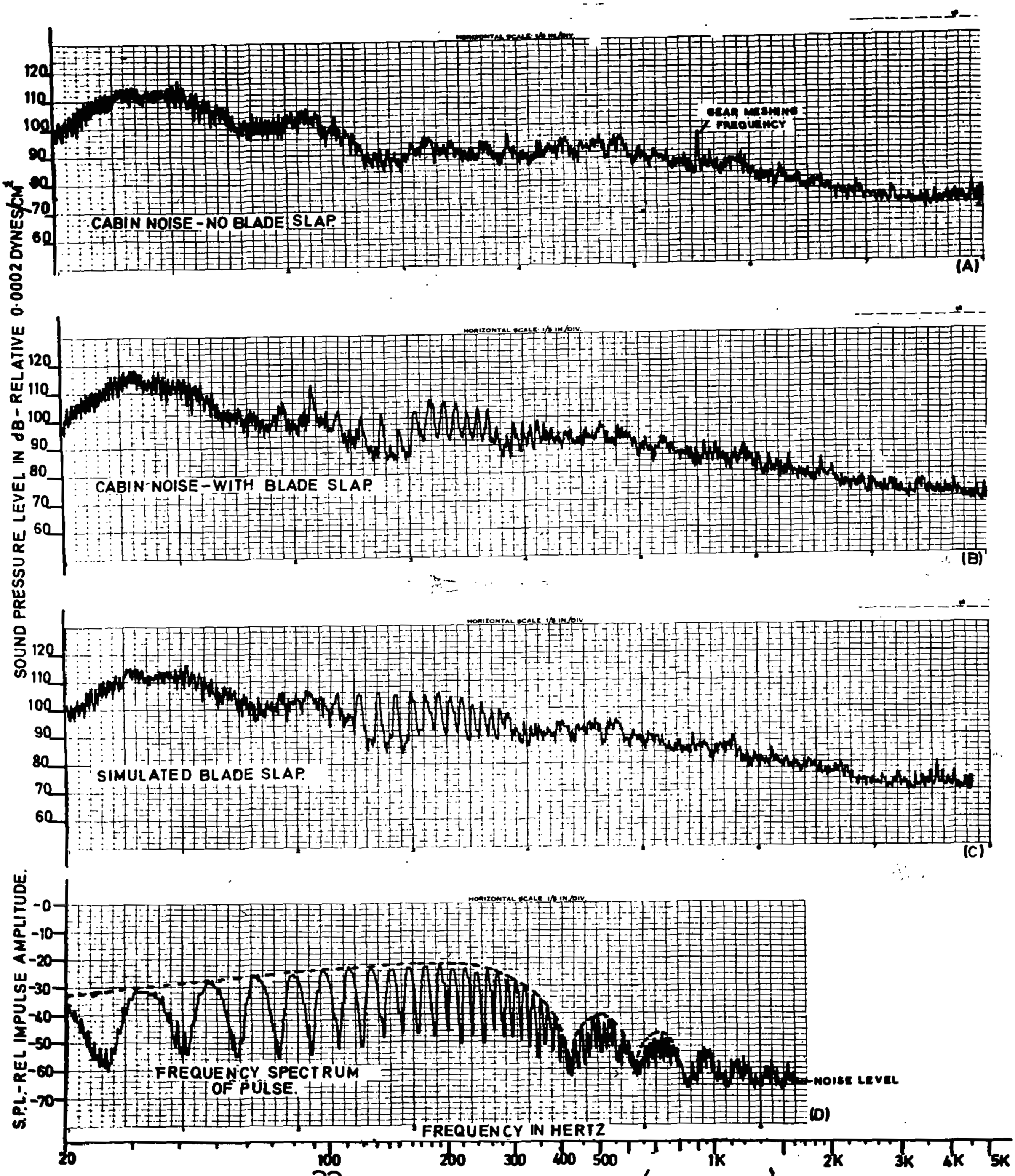


FIG 23 NARROW BAND ANALYSIS TRACES (WESSEX-MK 5)

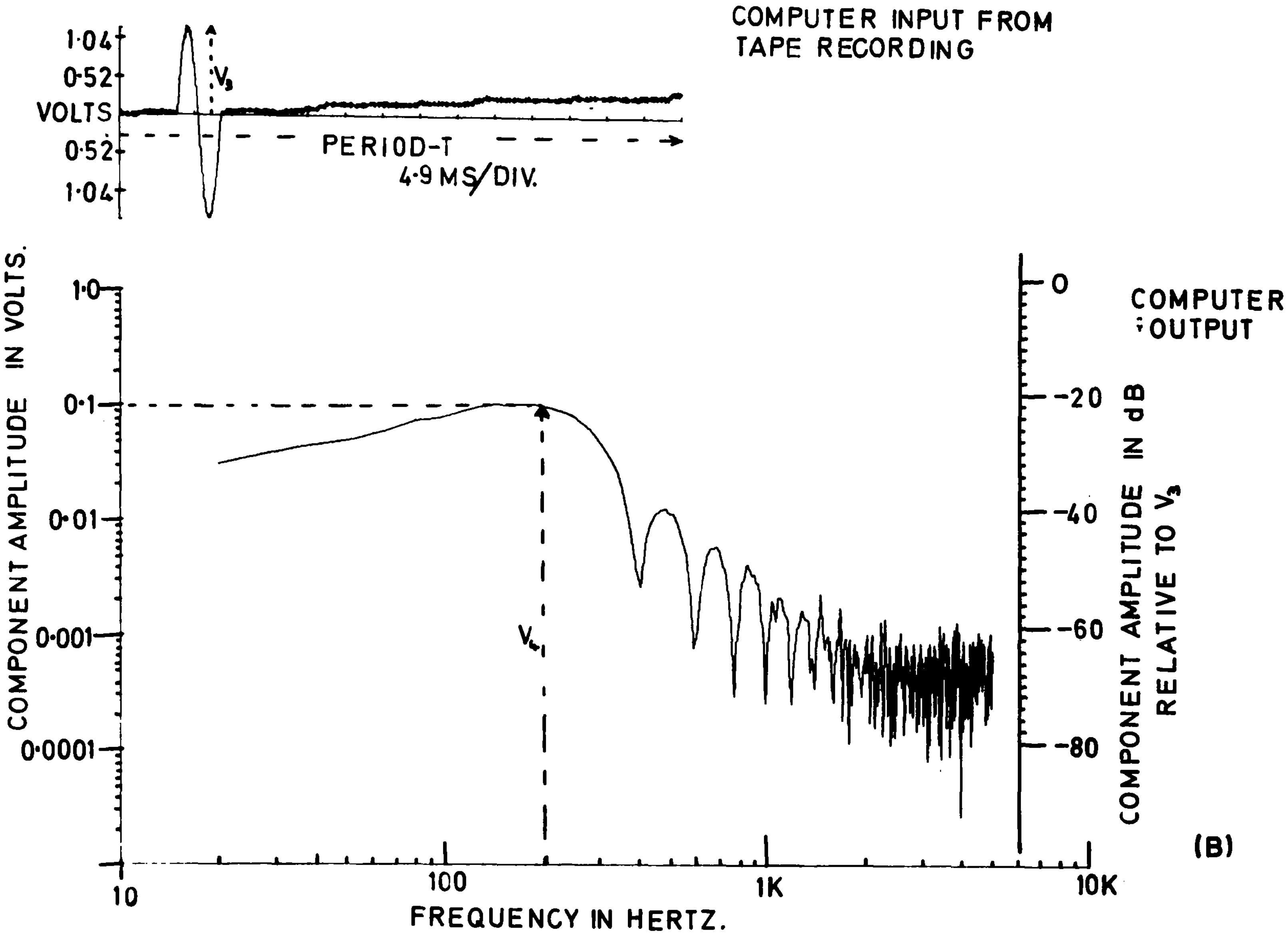
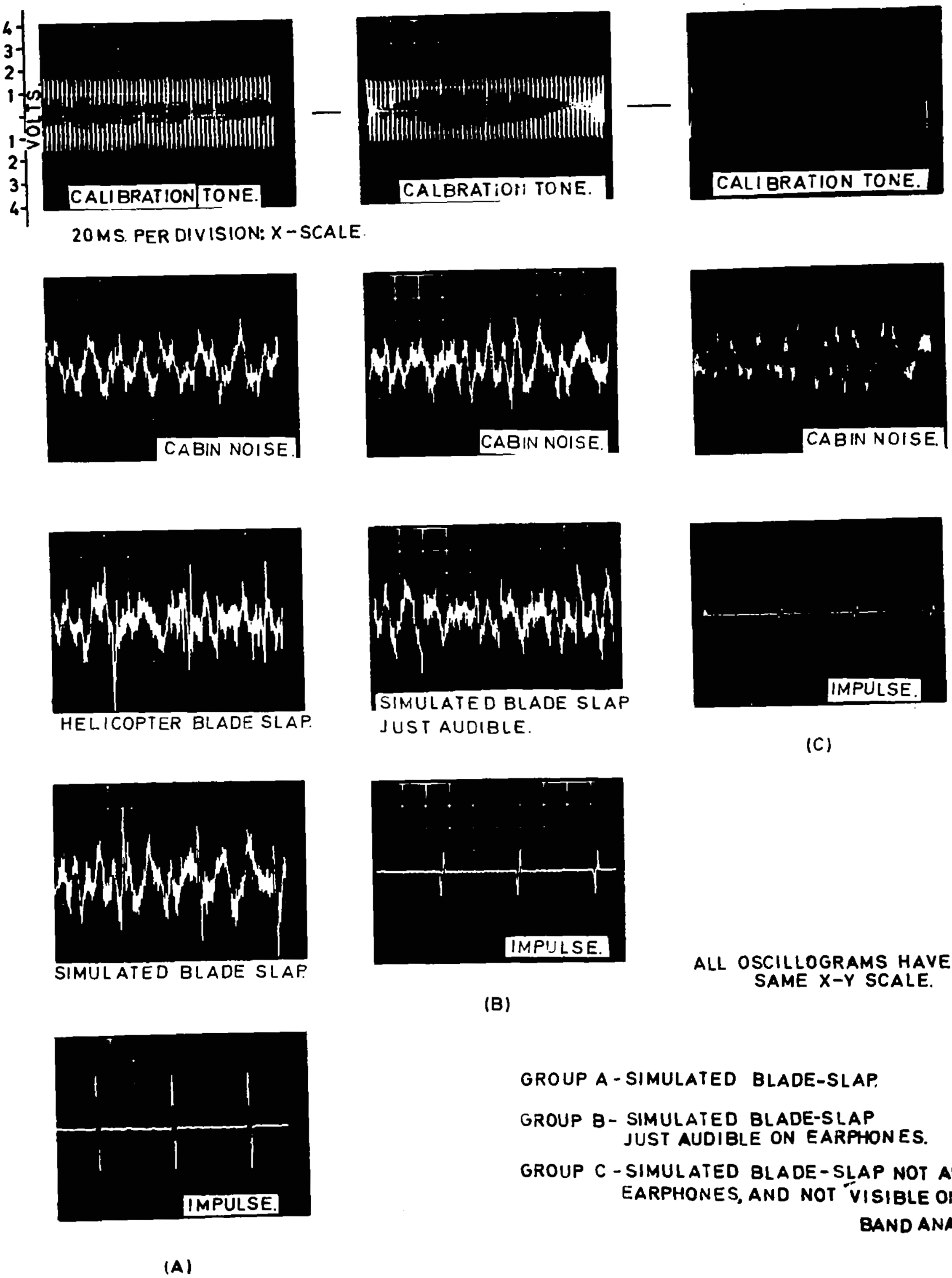


FIG 24 DIGITAL ANALYSIS OF PULSE WAVEFORM



ALL OSCILLOGRAMS HAVE THE SAME X-Y SCALE.

GROUP A - SIMULATED BLADE-SLAP.

GROUP B - SIMULATED BLADE-SLAP JUST AUDIBLE ON EARPHONES.

GROUP C - SIMULATED BLADE-SLAP NOT AUDIBLE ON EARPHONES, AND NOT VISIBLE ON NARROW BAND ANALYSIS.

FIG.25 OSCILLOGRAMS OF SIMULATED BLADE SLAP

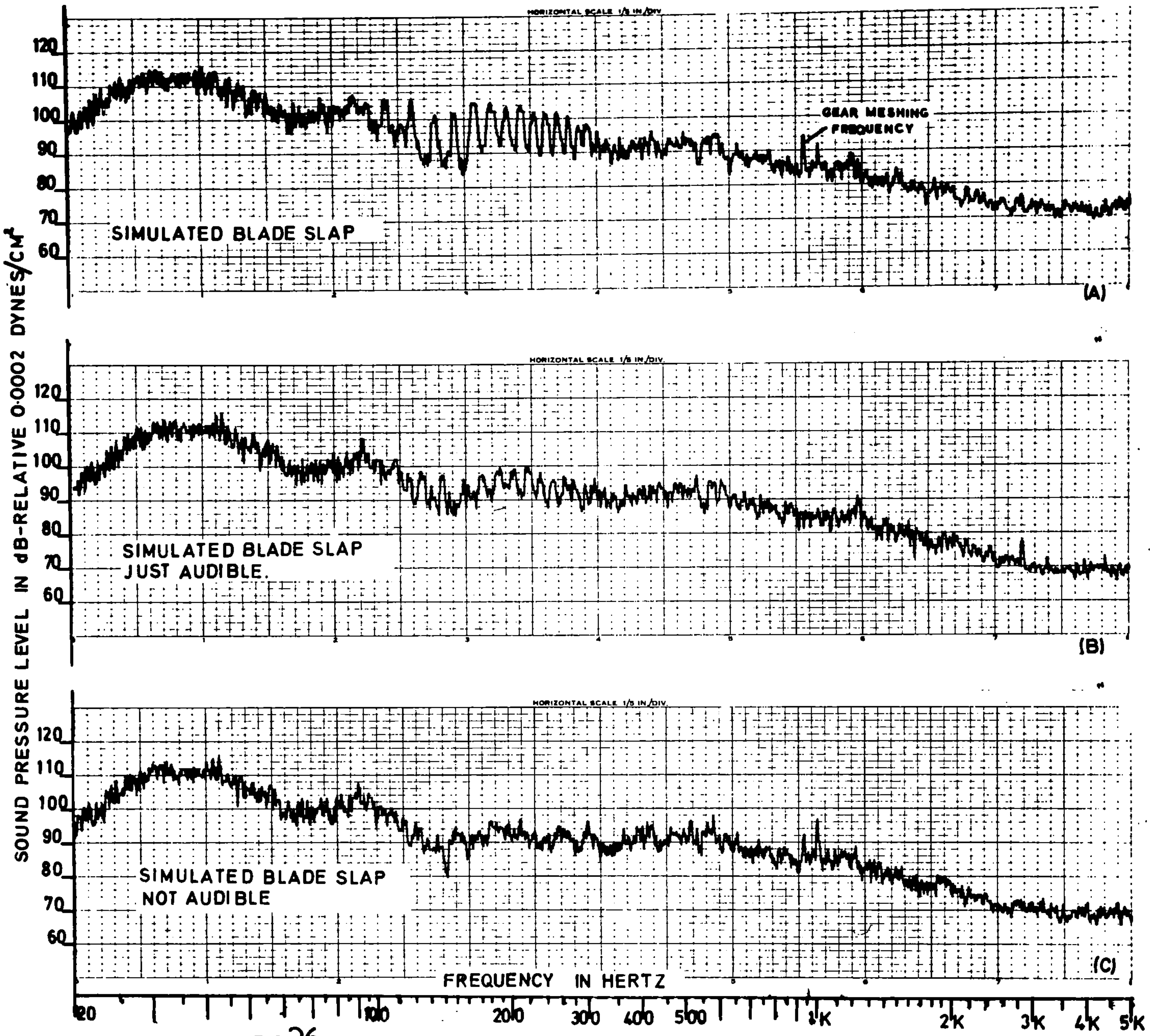


FIG 26 NARROW BAND ANALYSIS TRACES OF SIMULATED BLADE SLAP.

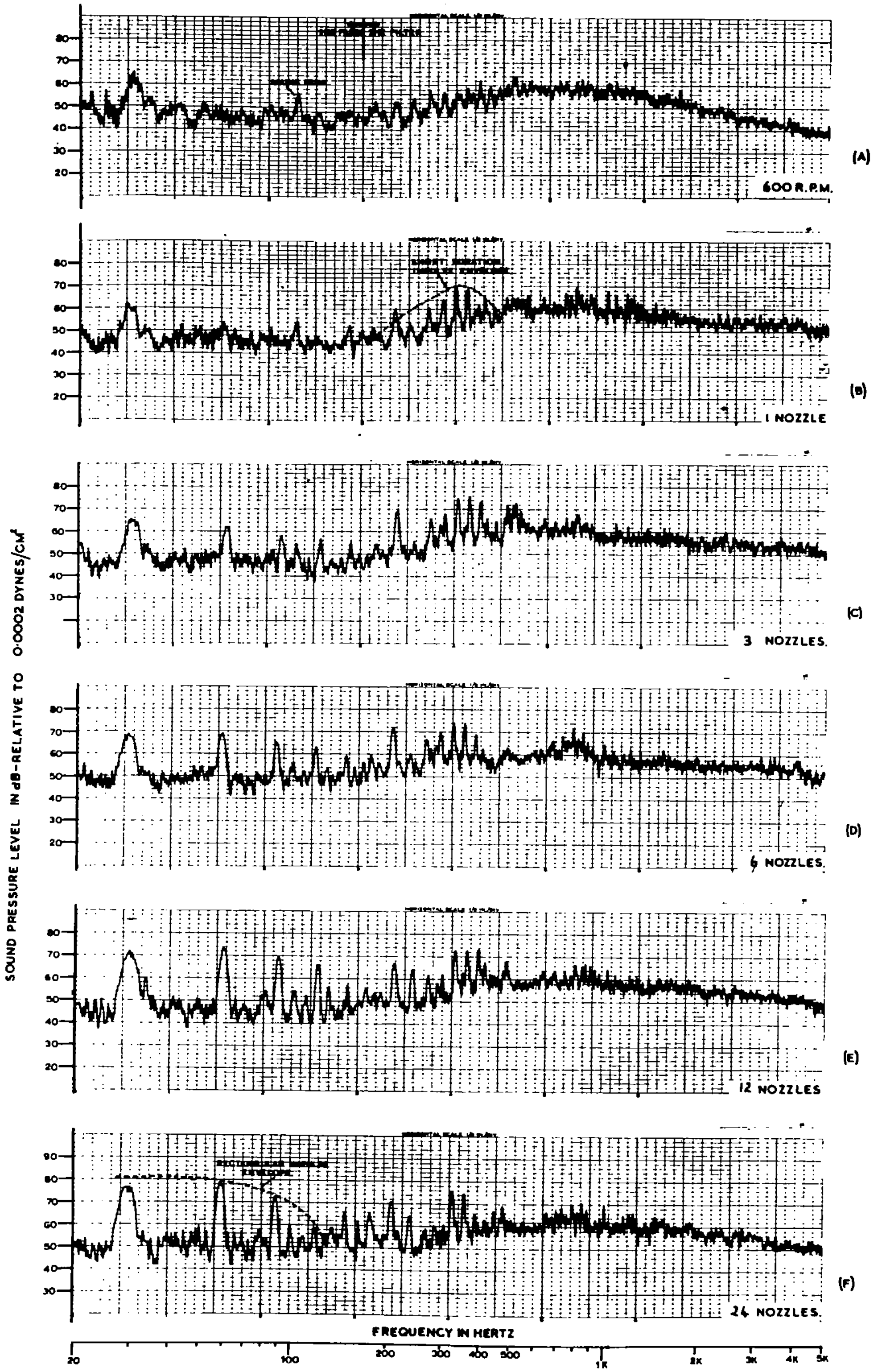


FIG. 27. Narrowband Analysis Traces of Transient Noise.

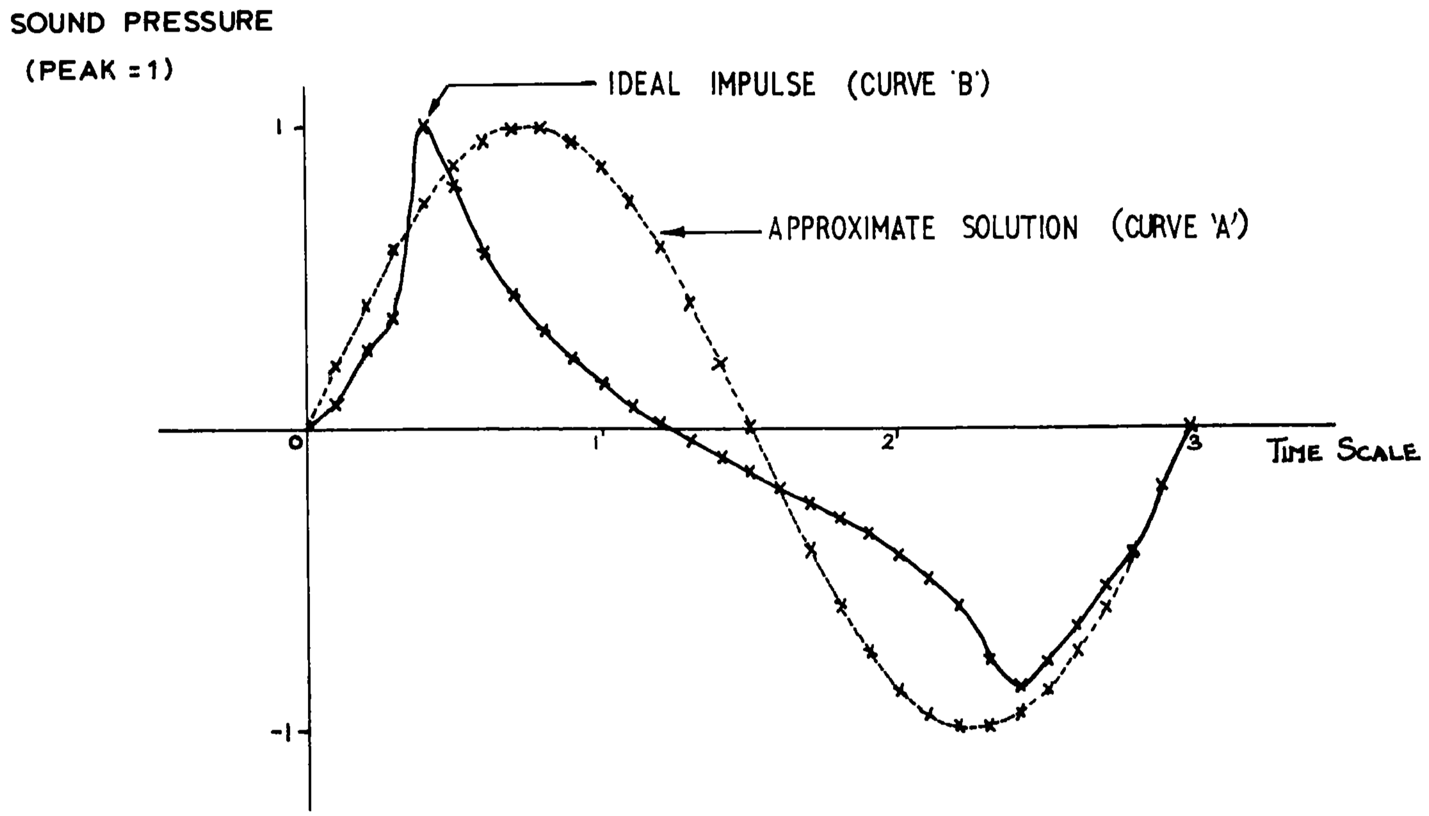


FIG. 28. BLADE SLAP — IMPULSE CHARACTERISTICS

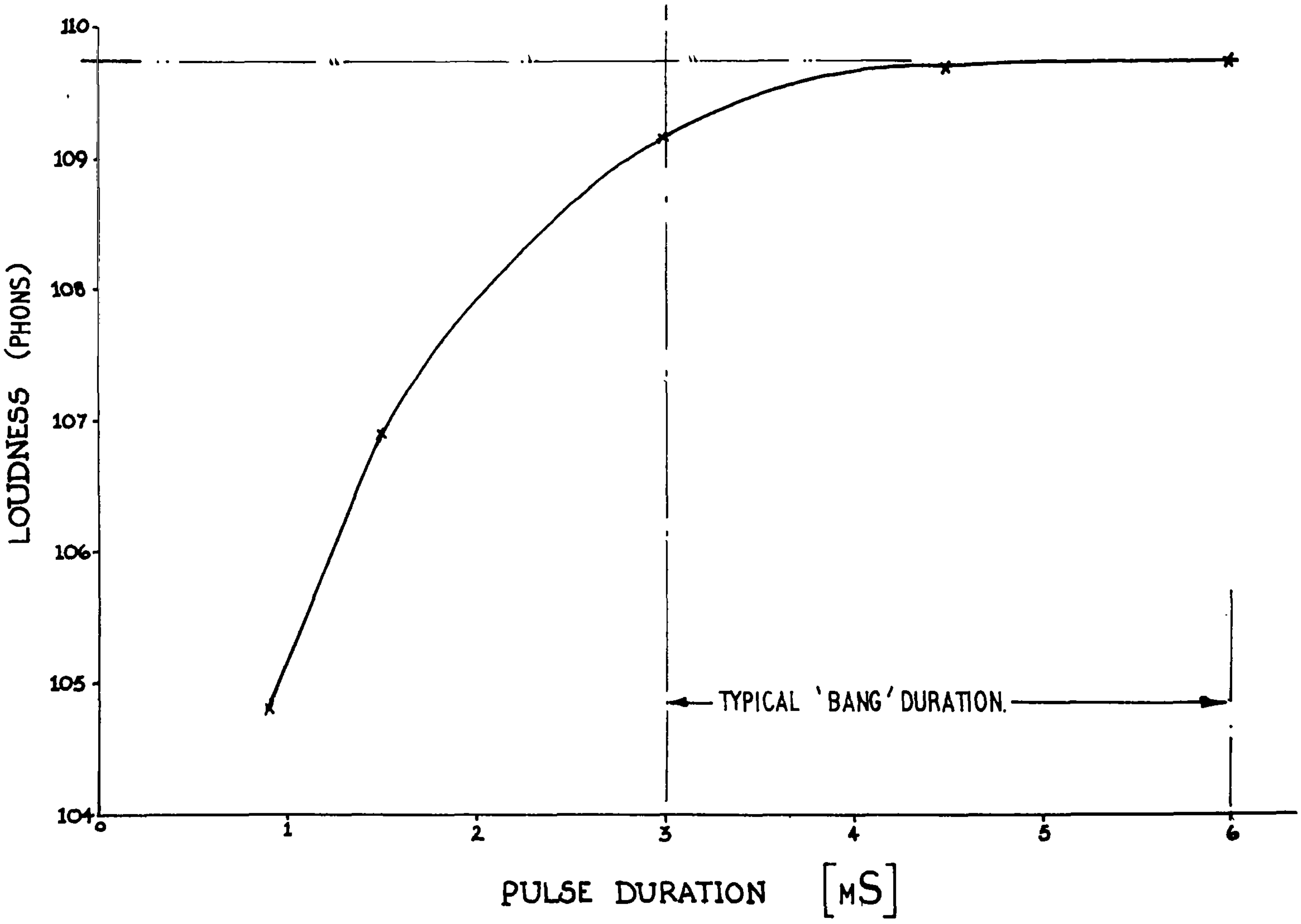


FIG. 29 LOUDNESS 'V' PULSE DURATION.

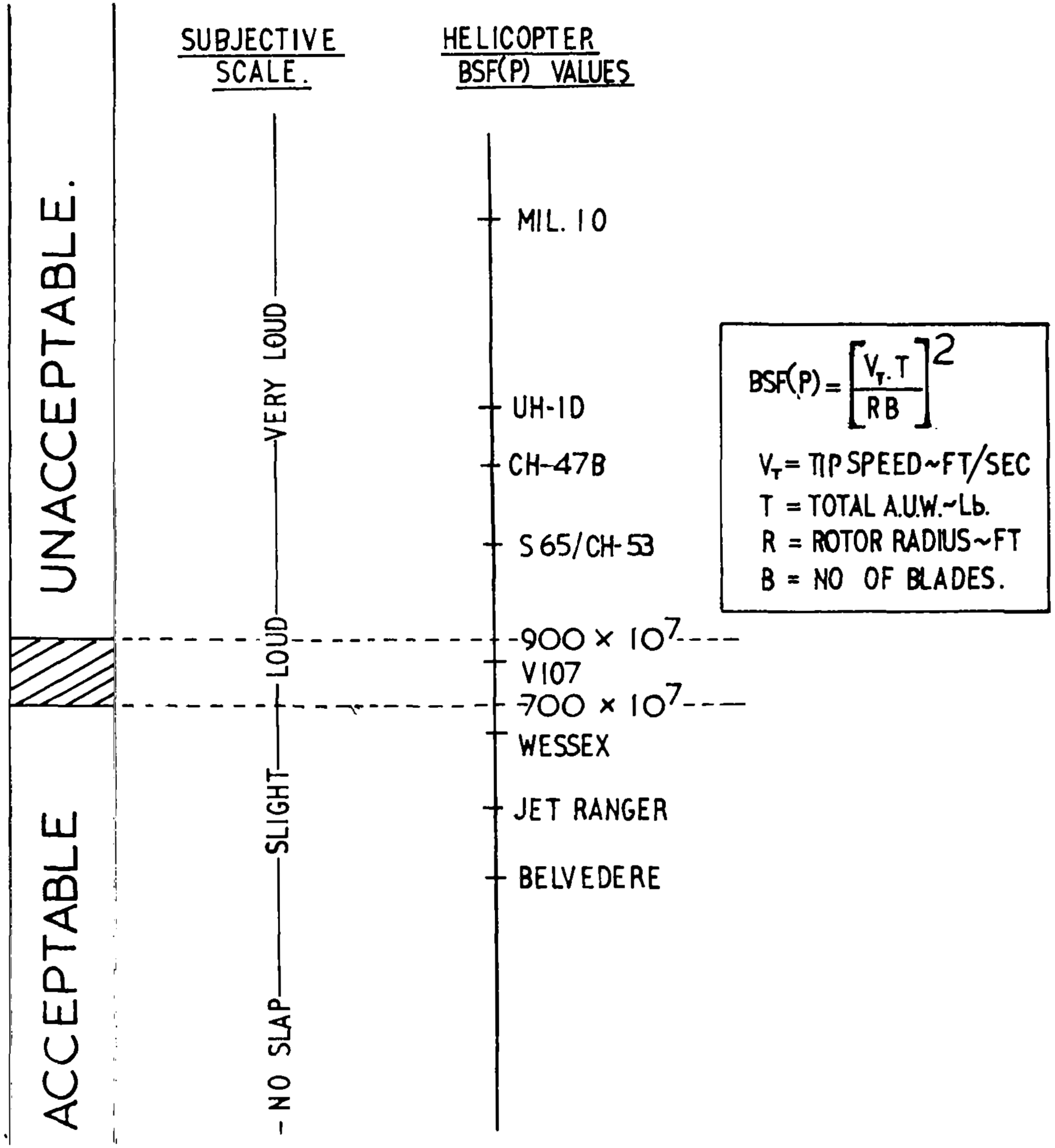


FIG. 30. BLADE SLAP CRITERION.- BSF[P]

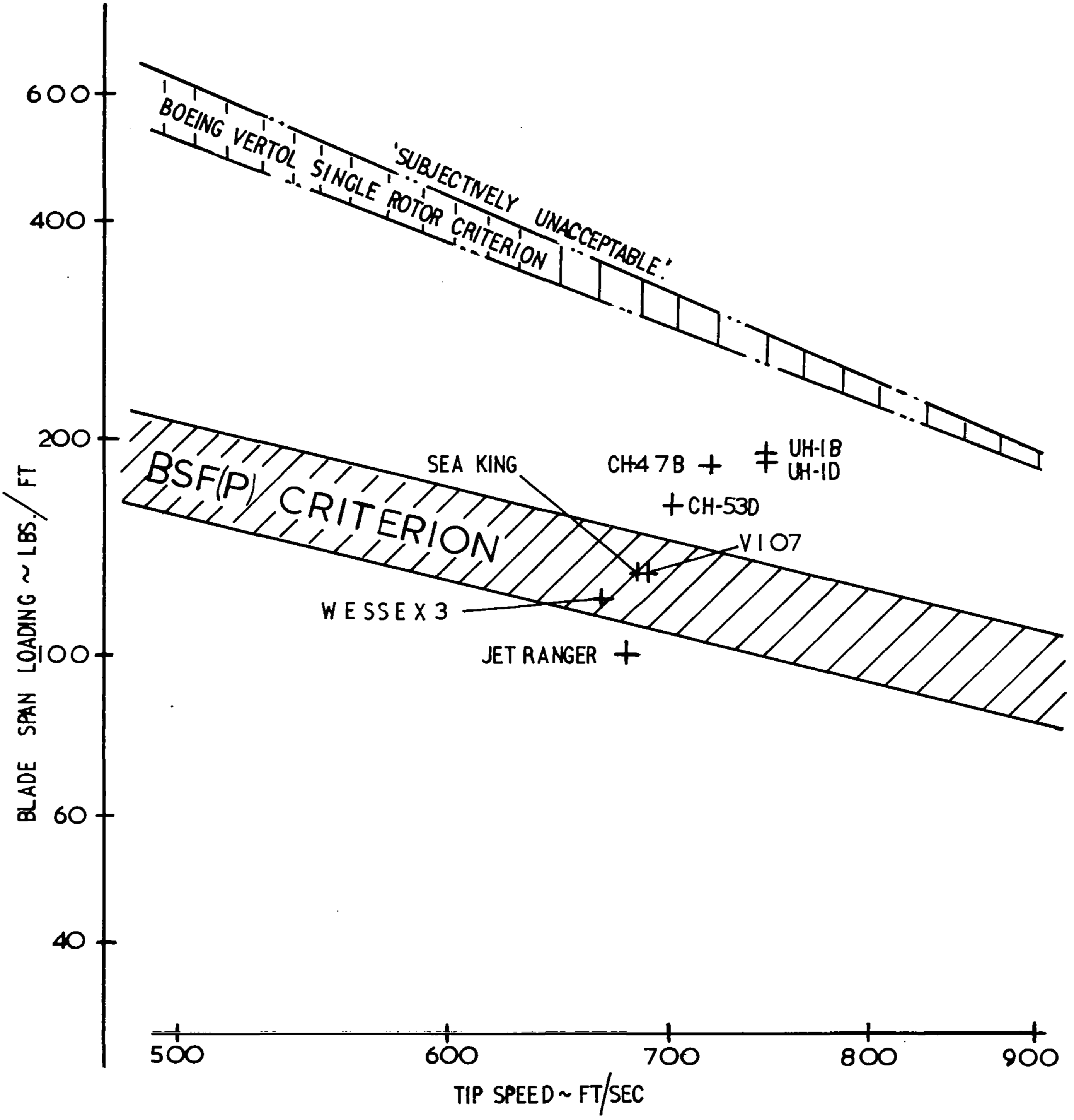


FIG.31. BLADE SLAP CRITERIA