UNIVERSITY OF SOUTHAMPTON

institute of sound and vibration research

I.S.V.R. Memorandum No. 311

HELICOPTER ROTOR NOISE
FINAL REPORT: PART II

EXPERIMENTAL STUDY OF ROTOR NOISE

by J.W. Leverton

June 1969

I.S.V.R. Memorandum No. 311

HELICOPTER ROTOR NOISE
FINAL REPORT: PART II

EXPERIMENTAL STUDY OF ROTOR NOISE

by J.W. Leverton

June 1969

HELICOPTER ROTOR NOISE

1st December 1965 to 30th November 1968

Research Sponsor: National Aeronautics and Space Administration, Washington D.C.

N.A.S.A. Grant N.G.R. -52-025-002

Research Contractor: Institute of Sound and Vibration Research, University of Southampton.

Contract No. 9634/32

Research Personnel:

Research staff: J.W. Leverton (Experimental)
Until 31st August 1968

H.K. Tanna (Theoretical)
From 23rd October 1967

Supervisor: Professor E.J. Richards
Until 3rd September 1967

C.L. Morfey
From 4th September 1967

Associate: Professor J.P. Jones

PREFACE

This report describes the experimental work carried out on the N.A.S.A. contract during the period 1st December 1965 - 30th November 1968. A review of the theoretical work has already been presented in reference 1.

In this report a summary of information presented in the series of status reports is given, together with results obtained during the last six month period of the contract.

The scope of this report is limited to presenting the experimental data collected and initial observations on the results. Because of a number of contributing factors it has not, in the time available, been possible to prepare for publication the series of NASA CR reports as originally planned. It is, however, intended that the author will continue preparation of the series of detailed studies, which will be submitted for publication as NASA CR reports in due course and/or issued as ISVR technical Reports.

The first report on blade slap (2) was published last year and a second report, giving the results of the experimental results related to blade slap, is now in the final stages of preparation.

LIST OF CONTENTS

List of figures

1. INTRODUCTION

A detailed experimental study was made using the I.S.V.R. rotor hover rig fitted with 1 to 4 blades. Data and initial observation on some of the results have already been reported in the Status reports which were issued bi-annually.

Although initially the main aim was to study broadband and rotational noise, the discovery of rotational peaks in the "vortex" region and the advent of rotational noise theories resulted in the main emphasis being placed on rotational (discrete frequency) noise.

To determine the applicability of the trends being found on the I.S.V.R. rotor rig, a detailed analysis was carried out on a series of full scale single rotor blade recordings obtained by Westland Helicopters Limited. Flight tests have also been re-analysed using a narrowband (2 Hz bandwidth)analyser to give real helicopter data.

2. EXPERIMENTAL RESULTS

The main emphasis to date has been on the rotational or discrete frequency noise. Prior to this report some of the results have been issued in the regular series of NASA Status Reports.

I.S.A.V. No. 194 (Status report for period 1st December 1966-30th May 1967), contained the following data:

1. 4 bladed ISVR Rotor Rig Results.
2. Single Bladed-Full Scale Results.
3. SRN4 Propellor Results.

Items 1 and 2 were presented in graphical and table form, while item 3 was only given in graph form. A more comprehensive form of the single bladed rotor full scale results is presented in reference 3.

The 4 Bladed Results quoted in ISAV No. 194 are limited to 8 blade passing harmonics; since this date the data have been re-examined and the study extended to cover 12 harmonics. The new data, together with that previously given in ISAV No. 194, is presented in Table 1. Similar results for the 3 bladed tests are given in Table 2.

In these tables the following notation is used:

- \- Indicates no 'peak' (discrete frequency) detected.
- $\overline{48}$ Indicates that it is not a clear peak.
- 54^{*} Indicates that the peak is less than 10 dB and more than 3 dB above the background (rig) noise.

In addition to 3 and 4 bladed rotor results, detailed analysis has been carried out on 1 and 2 blade tests. It was originally intended that these should be included in this final report: unfortunately a number of difficulties have arisen which have cast doubt on the validity of some of these results. For this reason it is considered that they should not be issued until a further detailed review has been made of the data and relevant analysis.

Frequencies associated with the 1 and 2 blades tests are, obviously, lower with the fundamentals being below the frequency range of conventional analysis equipment. In order, however, that information on the effects of the number of blades etc: could be obtained, equipment with a calibrated frequency response down to 8 Hz was used. Recordings were made on an FM tape recorder using a special low frequency F.E.T. Cathode Follower and analysis was performed using the Spectral Dynamics analyser fitted with a 2 Hz filter. Unfortunately this resolution is not sufficient to allow a 'peak' on the analysis to be positively identified as being rotational noise. In this context it should be remembered that a large number of 'low frequency' components are produced by the rig itself and consequently the rotor noise peaks can only be located by a detailed frequency analysis. In the case of the 1 and 2 bladed results the position is confused by the fact that the rig (background) noise spectra contains a range of frequencies which coincide with the rotational harmonics when using a 2 Hz filter for analysis. It appears that 'tape speedup' and then narrowband analysis will be required to separate the rig and rotor noise. This will only be successful however, if the rig and rotor noise "peaks" occur at slightly different frequencies. An initial investigation suggests this is the case, but it is not possible to analyse the results at the present time because the required equipment is not available at the ISVR. It is hoped, however, in the near future to use equipment at Westland Helicopter Limited, Yeovil for this analysis.

On the 3 and 4 blade tests the frequencies are higher and except for a few specific cases the "discretes" do not clash with any rig frequencies. In the 3 blade series of test the 700 RRPM condition is most affected and for this reason the quoted results for this condition should only be taken as an indication of the levels. The remainder of the results are correct, except for the limitation outlined previously.

3. BLADE LOADING

An estimation of the blade and total rotor loading has been made for all the conditions tested and the results are presented in the tables 3 and 4 for the 3 and 4 bladed rotor respectively.

Blade element (strip momentum) theory was used to calculate the 'ideal' spanwise lift and an allowance for the tip effect was then made empirically. Data given for a non twisted rotor in NACA 3688 (4) was used as a basis for the method. Figure 1 illustrates the method - the particular case for the 3 bladed rotor operating at 6° pitch, 500 RRPM is shown. A factor was applied to the results obtained using the blade element theory (at the calculation points) to reduce the value to the spanwise loading derived from NACA 3688.

Although this method has obvious limitations it is considered to be sufficiently accurate for this particular noise investigation. A similar estimation was made for the single blade full scale test programme, where actual thrust measurements were available. Figure 2 shows a comparison of the estimated and measured thrust levels. The "theory" tends to over estimate the measured values in all cases except the high pitch (15° cuff) and high speed conditions at 11° and 13° pitch setting. The 5° and 7° cuff measurements are suspect and it appears that the load cell was not zeroed before commencement of the test, with the result that the indicator "bottomed" on 500 lbs. In general, however, the agreement is relatively good, with the biggest error being in the order of 13%. It is worth noting that if these loadings are converted into noise units, (dB's) then the difference between using the estimated and measured loadings would be extremely small.

4. TORQUE MEASUREMENTS

The torque absorbed by the rotor for each condition is presented in Tables 3 and 4. From direct measurements of horse power of the driver motor, the horse power necessary to rotate the rig without blades is subtracted to obtain the appropriate "rotor H.P.". This has been converted into torque for convenience. The accuracy is considered to be good, except for the low speed/ low pitch setting cases where the power absorbed is small and it is extremely difficulty to read the relevant meters accurately.

Using blade element theory it is possible to estimate the torque in a similar manner to lift. In this case the agreement is not expected to be as good since it no not known how to account for the 'drag term'. Ideally the drag component at any pitch angle is simply a constant C_{Do}. A study of measured H.P. shows, however that it increases at a more rapid rate than can be accounted for by the contribution of the lift term. It has been shown experimentally by many investigations that in fact C_{Do} follows the form:

$$C_{Do} = D_{Domin} + x\alpha + y\alpha^2$$

where C_{Domin} is the value at zero pitch (lift), α the "effective" angle of attack and x and y constants. This explains the difference between the measurements and predicted values. Since, however, the solution for C_{Do} may be even more complex then given above, measured values of "torque" are used in any calculation and torque trends quoted have been obtained from direct measurements. The calculated values have not been included in this report since they are only of academic interest.

5. OBSERVATIONS ON EXPERIMENTAL RESULTS

It has proved impracticable to decide on a general graphical format for presenting the results. Thus rather then presenting a large number of figures, graphs are included which show particular trends of interest. Although the results shown are for specific cases, all the data have been reviewed to verify that the observations are general. Cross reference is also made between the ISVR model results and full scale measurements.

Details on the microphone layout relative to the model rig have been given previously (ISAV No. 194). It is worth noting that the main microphone was mounted 10^{o} below the rotor disc and 3 diameters away.

To date is has not been possible to compare the results with any theory except steady state Gutin calculations, since although detailed theoretical models are available, aeroydnamic data is lacking with the result that they cannot be applied to any particular configuration.

For convenience the following discussion is limited to the results obtained from the 3 bladed rotor tests. A study of the data presented in the tables will show, however that the 'four bladed rotor' results also follow the same trends.

If a detailed examination is made of the three bladed results it will be observed at some speeds, particularly 600 and 700 RRPM, that at the high pitch setting (8^{o} and above) an increase occurs in some of the harmonics which is completely out of keeping with the other harmonics. The increases are at the 3rd, 6th and 9th harmonics. The origin of this effect is not known, but it is thought that it could be the result of a 'flapping mode' resonance.

I. Simons in some of his aerodynamic studies carried out using the same rotor found similar effects when studying blade loadings. Since these "peaks" do not follow the trends associated with the other results they are not considered in the following discussions.

In studying the results it will be observed that there is considerable scatter in the levels quoted, except for the fundamental lower harmonics. This order of scatter is, however, common on the type of model tests carried out during the investigation. For this reason it is often necessary to consider the general trend rather than compare specific results.

5.1 Rig Results (3-Bladed Rotor)

At zero and low pitch the fundamental frequency component rises at a much more rapid rate, relative to tip velocity, than the higher harmonics. Figure 3 plots SPL vs Harmonic for a range of higher tip speeds at 2^{o} pitch. It will be observed that the higher harmonics are "scattered" about a mean amplitude while the fundamental increases directly with rotor speed above 6/700 RRPM. The results for 0^{o} and 2^{o} pitch are plotted as a function of rotor RRPM in Figures 4 and 5 respectively. It will be noted that there is not sufficient data available at 0^{o} pitch to draw different trends - it is clear however from <u>all</u> the results presented that the 0^{o} and 2^{o} cases are very similar and thus 0^{o} and 2^{o} pitch can generally be discussed together. The main difference between the two conditions is that 0^{o} pitch the second harmonic appears to follow the same trends as the fundamental, while at 2^{o} pitch the second harmonic follows the trend of the other higher harmonics.

The 'Gutin' prediction for the fundamental at low pitch, where the torque term dominates, shows an increase according to V^{10} law. As expected ($V^{2\beta}$ + 4 since drag $\propto V^{2}$). It will be observed that the fundamental increase at a higher rate than given by 'Gutin' at rotor speeds above 600 RRPM with the experimental increase being in the order of V^{18} (54 dB/doubling of speed).

The higher harmonics on the other hand appear to fluctuate around a mean as shown on Figure 5. There is, however, an indication of a 'drop off' of level with increasing harmonic number this is also shown in Figure 3.

The effect of pitch on the fundamental in terms of rotor speed is illustrated in Figure 6. Above 600 RRPM, the majority of results show the same trend although the 8^{o} pitch condition tends to suggest a higher rise rate. Power limitations of the rig prevented results being obtained at high pitch settings/high speed.

At the higher pitch setting the higher noise harmonics also follow the trend set by the fundamental, particularly at rotational speeds above 600 RRPM. This is illustrated in Figure 7.

The relationship between the noise and lift/torque also appears interesting. At high tip speeds the fundamental, and to some extent the second harmonic, remains constant with increase in pitch (which produce an increase in both torque and lift). The high harmonics on the other hand increase quite rapidly with pitch. Figures 8 and 9 illustrate these effects. At the low speeds the fundamental and all the harmonics appear to follow the same trends with pitch as illustrated in Figure 10 for the 500 RRPM case.

5.2 Full Scale Results (1-Bladed Rotor)

The fundamental on the single bladed full scale tests (3) was found to agree well with the trends predicted using the 'Gutin' relationship. Figure 11 show a comparison of the 'Gutin' and measured values. It will be noted that the 'Gutin' theory overestimated the values in all cases with the main difference occuring at the low pitch settings. Part of the discrepancy could be due to the choice of effective radius for the Gutin calculations (0.8 x tip radius).

The high harmonics, on the other hand, do not appear to be correlated with either thrust or torque and are practically independent of these parameters as illustrated in Figure 12. It will be observed that the increase on the 9th harmonic is 2 dB. Harmonics up to the 15th also follow this trend. In terms of velocity all the harmonics appear to follow the same general trends as shown in Figure 13.

'Profile drag' or thickness effects seem to be the only parameter which could explain these results. It is of interest to note that results presented earlier for the ISVR rig show the fundamental and 2nd harmonic to be practically constant in level, as pitch was increased at the higher rotor rotational speed (1000 RRPM - 418 ft/sec tip speed).

In the case of the three-bladed results the fundamental follows the same trends as the 2nd/3rd harmonics of single blade tests. In this case there was no correlation with the 'Gutin' value except at the high pitch settings. The reason for the difference in the trends of the fundamental for the two tests is not known, but it is of interest to note that the 3rd harmonic for the single bladed tests is of the same form as the 1st harmonic for the three bladed tests (i.e. at the same mB number).

Although it is not definite, it does appear from these results that there is another mechanism in addition to the 'fluctuating load mechanism' involved in rotor noise generation. Alternatively it could be that the fluctuating blade loads are completely independent steady thrust and torque on the rotor. It is difficulty, however to understand the velocity trends (Figure13) if latter reason is used to explain the results.

6. HELICOPTER RESULTS

Considerable data on the noise produced by real helicopters has been collected and analysed over the three years of the contract. Although the majority of this could not be used for detailed studies it has provided invaluable back up material. Much of the data is, however, not of direct interest to the investigation outlined in this report and for this reason helicopter results have only been used to illustrate various aspects of helicopter rotor noise. Some of this data has already been presented in previous status reports and it seems fair to state that the first results showing the large number of discrete components that can occur in the region traditionally taken as being 'broadband' were produced at the ISVR in 1965. This discovery, of course, helped to stimulate many of the theoretical studies outlined in reference 1.

It is now a well established fact that rotational noise harmonics (discrete frequencies) occur in the broadband (vortex) noise region. For this reason it would appear that some authors have considered discrete frequency noise to be the most important from the point of view of the 'overall noise' level in all cases. It is clear, however, from experimental results that broadband noise of very significant levels is produced by some rotor configuration.. In this section of the report an attempt is made to illustrate the relative importance of these two main types of rotor noise.

It was known from tests on the ISVR single rotor rig that broadband noise, free from discrete components, could be obtained provided the turbulence and/or the re-circulation around the rotor was small. Unfortunately this could only be obtained in the laboratory with low lift conditions. Since it was desirable to know if these 'peaks' also occured in the broadband - vortex region when the lift on the blade was high, a carefully controlled test was carried out using a Wessex helicopter. Recordings of the Wessex , hovering at an altitude of 40 ft. and 200 ft. from the microphone, were made in normal wind conditions (wind speed about 8 knots) and again with a very low wind speed environment (less than 2 knots). The narrow band analysis results are shown in Figure 14;trace (a) shows a typical

1.5% narrow band analysis while (b) and (c) are $\frac{1}{2}$ Hz bandwidth analyses of the 'less than 2 knot' and '8 knot' wind conditions respectively. It will be noted there are many discrete components in the light wind case, trace c, and that the 'broadband' noise is practically the same level for both conditions. Further test results have shown that 'wind' is not the controlling parameter, and that the use of different helicopters and/or pilots produces the same order of differences in the spectrum. The two results reproduced do however tend to show the minimum and maximum discrete frequency noise content in the broadband region, for this particular helicopter under normal operation conditions.

This clearly illustrates the effect of small scale turbulence and the occurrence of discrete frequencies in the broadband region. This does not imply that the rotational noise components are more important to the overall noise level for the condition shown in trace (c), since if the energy is computed for a wide frequency range it will be greater from the 'broadband' than the discrete components.

It is worth noting that a 1.5% or 10 Hz analysis of the two conditions gives practically identical spectrum shapes, with the '8 knot case' having slightly higher levels. Thus if a semi-narrow band analyser is used to measure broadband noise the maximum level detected could be due to the discrete components. This could explain the apparent anomalies in the 'broadband velocity laws' which have been found on certain helicopters.

On other rotor configurations rotational noise will dominate both the overall level and the narrow band spectrum. A number of examples are illustrated in the narrow band analysis results reproducted in Figure 15. Trace (a) is for a hovercraft propeller operating at moderate thrust, trace (b) shows the results from a Bell Helicpter in flight, and trace (c) is an analysis of one of the ISVR test rigs. All the recordings were taken at angles in the range 105/120° from the direction of thrust and it is clear that in each case the 'overall levels' are dependent on the rotational noise components. It is also of interest to observe the large number of rotational components that can be detected on the latter two traces. From the results on Figures 14 and 15 it is obvious that either rotational (discrete frequency) or broadband noise can dominate the overall noise level, and in many cases the two types of noise can be equally important.

In discussing rotational and broadband noise, it should be remembered that the results do not imply that the two categories of noise are produced by separate mechanisms. Experimentally, howev r, it is necessary at the present time to consider the two types separately since they appear to follow different trends and theories are not sufficiently developed to allow the 'total noise' concept to be used.

An extensive study has been made of experimental data available, to determine if the rotational noise spectra follow any general pattern. According to theoretical considerations the results should be studied as a function of 'mB' and not in terms of blade passing harmonics m. To date, however, the majority of results available are for 3 and 4 bladed rotors and it has only been possible to correlate the results relative to the fundamental frequency (first blade passing harmonic).

The envelope of the results is presented in Figure 16. Although the envelope applies in general to multibladed rotors operating at moderate tip speeds, some results for a full size single bladed rotor (3) show a similar pattern. A comparison has also been made between the Gutin 1st harmonic value, at an angle of $110/120^{\circ}$ from the direction of thrust, and measured levels of the fundamental. Good agreement was found to occur provided the thrust was large compared to the torque force, as in normal operating conditions.

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to the two supervisors listed below for thier help and guidance throughout the investigation. The supervisors were

Professor E.J. Richards, now Vice-Chancellor, University of Technology, Loughborough, formally Director of Institute of Sound and Vibration Research (Period 1st December 1966-September 1967).

Mr. C.L. Morfey (Period September 1967 to date).

The author would also like to thank the following:

1. N.A.S.A. for financial support of this investigation.
2. Westland Helicopter Limited, Yeovil, for making freely available fill scale test and flight data and in particular Mr. O.L.L. Fitzwilliams, Chief Engineer (Research), for his help and interest shown in the work.
3. The following helicopter manufacturers for supplying data, in the tape form, on various helicopters.
   (a) Bell Helicopter Company, Fort Worth, Texas.
   (b) Boeing-Vertol, Morton, Pa.
   (c) Sikorsky Aircraft Company, Stratford, Conn.

References

1.	H.K. Tanna	I.S.V.R. Memorandum No. 283. Helicopter Rotor Noise - Final Report : Part 1 March 1969.
2.	J.W. Leverton	Helicopter Noise - Blade Slop. Part 1: Review and Theoretical Study NASA CR-1221. October 1968.
3.	J.W. Leverton R.E. Couser	Helicopter Rotor Noise Single Bladed Rotor Results. ISAV Memo. No. 169, June 1967.
4.	J.P. Robbott	Static Thrust Measurements of the Aerodynamic Loading on a Helicopter Rotor Blade. NACA Tech. Note 3688 - July '56.

TABLE 1

3 -Bladed Rotor - ISVR Rig

PITCH	RRPM	HARMONIC ORDER												dB LIN
		1	2	3	4	5	6	7	8	9	10	11	12	
0°	300	-	52*	47*	40*	43*	45*	47*	$\overline{40}$	45*	50*	44*	44*	68
	400	51	48*	44*	42*	$\overline{46}$	45*	45*	42*	$\overline{39}$	40*	$\overline{40}$	40*	69
	500	46	47*	44*	46*	38*	44*	44*	44*	$\overline{41}$	$\overline{37}$	42*	40*	69
	600	48	35*	46*	44*	44*	$\overline{44}$	46*	$\overline{40}$	42*	42*	42*	43*	71
	700	49	46*	46*	44*	$\overline{44}$*	46*	43*	42*	46*	46*	44*	44*	74
	800	61	51	43*	46*	46*	48*	44*	46*	45*	43*	44*	43*	75
	900	71	56	$\overline{42}$	$\overline{44}$	48*	44*	46*	44*	45*	44*	44*	47	78
	1000	78	62	45*	$\overline{47}$	$\overline{44}$	48	46*	46*	$\overline{44}$	44	46	46	84
2°	300	-	50*	55*	48*	46*	52*	49*	$\overline{40}$	$\overline{46}$	49*	$\overline{53}$	44*	68
	400	-	51*	54*	47*	44*	51*	$\overline{47}$	40*	44*	52*	45*	44*	69
	500	50	54*	50	50*	47*	$\overline{46}$	51*	$\overline{40}$	47*	39*	$\overline{38}$	$\overline{40}$	68.5
	600	48*	44*	46*	45*	44*	50	44*	42*	40*	40*	46*	40*	69.5
	700	52	50*	54*	53	57	48*	47	47*	48	46*	48*	45*	71.5
	800	66	60	62	54*	51	50	50	55	55	48*	41*	47*	74.5
	900	74	64	54	57	59	50*	51	52	52	52	50*	50*	77
	1000	80	62	59	55	57	57	52	50	52	49	51*	48*	82
4°	300	-	47*	54*	45	$\overline{46}$	$\overline{52}$	52	$\overline{45}$	$\overline{47}$	$\overline{53}$	$\overline{48}$	49*	68
	400	-	42*	48*	48	52*	49*	52	-	50	$\overline{46}$	52	44*	69
	500	54	59*	60	54	53	50*	58*	52	54	50	49	48*	70
	600	57	56	55	54	52*	57	55	52	48	50	49	54	72
	700	56	66	66	66	65	59	58	54	56	60	56	55	75
	800	67	66	63	68	66	62	60	60	64	55	56	58	79
	900	73	70	57	60	58	54	58	55	50	52	48	48	82
	1000	79	67	61	62	67	65	62	60	60	57	57	55	84

PITCH	RRPM	HARMONIC ORDER 1	2	3	4	5	6	7	8	9	10	11	12	dB LIN
6°	300	-	47*	53*	46*	46*	47*	46*	-	47*	53*	-	44*	69
	400	-	45*	54*	46*	48*	54*	48*	48*	-	51*	51*	47*	71
	500	53	64	56	61	53	47*	56*	50	52	49	48	47	73
	600	57	52	60	57	52*	56*	53*	54	53	52	57	54	75
	700	57	64	67	65	64	58	58	57	57	57	56	55	78
	800	66	68	62	62	63	64	57	63	60	58	57	56	81
	900	74	74	69	70	69	65	68	67	62	64	61	60	84
8°	300	-	39*	38*	37*	40*	$\overline{36}$	40*	38*	37*	41*	-	36*	70
	400	-	42*	55	48	53	48*	52	39*	40	37	42*	38*	72
	500	57	66	64	62	51	54	55	52	55	52	47	50*	74
	600	58	56	65	61	54	61	57	58	59	57	58*	56*	78
	700	61	71	76	70	66	62	64	59	62	58	59*	60*	83
	800	77	77	76	79	74	75	76	80	73	70	72*	70*	84
10°	300	-	48*	48*	47*	$\overline{45}$	$\overline{48}$	47*	46*	45*	50*	-	45*	69
	400	-	42*	52*	50*	57	51	52	52*	51	50	50	52	75
	500	60	61	62	60	52*	53	54	54	56	56	49	52	76
	600	62	59	74	61	55	63	57	58	58	60	55	54	80
	700	64	71	72	67	68	62	64	58	61	59	60	58	84
12°	300	-	49*	55*	47*	48*	$\overline{52}$	48*	49*	47*	51*	45·	45*	69
	400	-	46*	55*	49*	$\overline{47}$	57	52*	53	$\overline{52}$	$\overline{51}$	48*	$\overline{50}$	75
	500	59	70	65	64	54	55*	60	56	59	59	57	58	80
	600	64	59	73	67	62	66	65	63	64	64	60	60*	83
14°	300	-	48	56	51	48*	50*	50*	50	48*	51	$\overline{47}$*	$\overline{48}$*	69
	400	-	47	58	56	59	52	57	56	55	54	55	$\overline{52}$	76
	500	59	70	62	65	$\overline{59}$	58	60	$\overline{63}$	59	60	$\overline{56}$	57*	81

Note $\overline{46}$ indicates that it is not a clear peak

- indicates no peak

* peak is not 10 dB above background level

All levels are dB rel. 0.002 DYNES/CM^2

TABLE 2

4 - Bladed Tests - ISVR Rig

PITCH	RRPM	HARMONIC ORDER												dB LIN	dB.A
		1	2	3	4	5	6	7	8	9	10	11	12		
0°	300	$\overline{48}$	$\overline{57}$	$\overline{52}$	$\overline{45}$	$\overline{47}$	$\overline{60}$	48	-	50	55	50	42	67	60
	400	-	-	-	-	-	-	-	46	-	46	47	47	69	63.5
	500	-	46½	-	-	48	44	46	48	50	50	50	49	71	67.5
	600	46	-	49	-	48	48	52	52	51	55	54	52	75	71.5
	700	52½	-	-	-	49	50	53	54	56	54	56	-	77	75.5
	800	65½	60	-	49	52	56	56	58	59	58	-	-	81	79
	900	73	53	-	54	57	58	58	57	-	-	-	-	85	83
	1000	73	60	56	58	58	59	59	-	-	-	-	-	87	85.5
2°	300	-	58	52	-	-	57	-	-	-	-	-	-	69	66.5
	400	53	-	-	-	-	-	-	48	-	-	-	-	70	66.75
	500	48½	-	-	-	53	44	45	-	49	-	-	-	70.5	67
	600	53	-	55	-	52	45	48	51	51	47	45	45	71.5	68.5
	700	58	-	60	-	53	-	53	52	57	51	52	$\overline{48}$	74	71.5
	800	65	59	57	58	58	59	59	56	51	53	56	53	77	75
	900	73½	63	58	61	66	64	61	56	59	59	57	52	81	77.5
	1000	71½	70	67	71	66	65	63	67	61	61	$\overline{57}$	$\overline{57}$	83	80
4°	300	-	-	52½	-	-	-	48	-	-	43	45	-	71-72	65.5
	400	67	-	-	57	48	54	46	47	48	48	45	43	71	65.5
	500	-	62½	59	-	-	$\overline{38}$	37	34	36	33	33	32	71.5	67.5
	600	59	59	65	59	56	60	57	58	52	54	51	49	75	70.5
	700	-	-	69	62	62	63	61	63	61	55	54	54	78.5	74
	800	71	65	67	66	68	68	62	61	58	60	59	-	81	77
	900	76½	72	68	67	64	69	64	61	-	-	-	-	84.5	80
	1000	7	76	72	75	71	71	70	67	67	64	64	63	88	82

TABLE 2 contd.

PITCH	RRPM	HARMONIC ORDER												dB LIN	dB.A
		1	2	3	4	5	6	7	8	9	10	11	12		
6°	300	50	44	43½	-	-	47	-	-	-	-	44	-	70	66
	400	57	58½	48	57	52	-	46	47	48	46	49	44	76	66.5
	500	66	63½	62	60	63	65	60	58	55	53	54	56	75	68.5
	600	-	63	68	65	67	64	62	65	62	60	53	54	79	72
	700	67½	76	72	65	67	65	68	62	63	61	60	-	81	76
	800	75½	69	75	70	71	74	71	65	65	64	-	-	84.5	79
	900	79½	80	74	70	72	73	68	64	-	-	-	-	87	82.5
8°	300	-	46	42½	45	-	48	45	-	48	43	47	44	70.5	68
	400	65	43	-	46	44	-	-	-	-	42	41	-	75	68.5
	500	66	57½	57	55	55	52	53	52	50	49	48	50	76	70
	600	66	68	73	69	68	61	61	63	62	60	57	53	79	73.5
	700	68	78½	78	69	68	68	66	65	64	63	62	62	83	77.5
	800	71	71	68	66	67	68	66	62	59	61	57	60	86	81.5
10°	300	52	47	47½	47	-	48	-	-	-	47	44	45	71.5	66
	400	75	-	-	55	56	-	50	50	53	52	51	52	77-82	68.5
	500	68½	62	-	61	58	60	58	57	57	52	52	-	77-78	70
	600	68	67	65	66	65	60	60	63	59	57	54	51	81	73
	700	68	79½	73	64	67	66	64	63	65	60	62	60	85.5	77
12°	300	53	47	49½	-	-	51	47	-	45	42	44	46	69	64
	400	75½	54½	53	55	54	53	52	51	52	51	49	-	77-79	68
	500	74	65½	63	62	60	58	58	57	58	54	55	54	80	72
	600	65	67	65	67	66	60	63	66	61	61	57	53	83	75.5
14°	300	57	49½	48½	-	-	49	53	51	46	-	-	-	70-72	61.5
	400	75	-	62	-	59	-	56	56	56	-	-	-	79	68.5
	500	73	66	67	67	66	65	62	61	$\overline{62}$	60	$\overline{62}$	-	82	76.5

Note $\overline{48}$ indicates that it is not a clear peak

\- indicates no peak

All levels are dB rel. 0.0002 DYNES/CM^2

TABLE 3

PITCH	RRPM	LIFT BLADE	TOTAL LIFT.lbs	H.P.	TORQUE lb.ft.
0°	300			0.15	.02506
	400			0.28	.04517
	500			0.49	.06678
	600			0.75	.08665
	700			1.17	.12187
	800			1.63	.15158
	900			2.23	.18739
	1000			3.1	.24221
2°	300	0.57	1.71	.174	.03206
	400	1.02	3.06	.284	.04617
	500	1.58	4.76	.507	.06978
	600	2.28	6.84	.838	.09965
	700	3.27	9.4	1.2	.12587
	800	4.05	12.15	1.72	.16058
	900	5.14	15.42	2.39	.20339
	1000	6.34	19.02	3.1	.24221
4°	300	1.4	4.2	.192	.03706
	400	2.5	7.5	.387	.06917
	500	3.88	11.7	.69	.10178
	600	5.61	16.3	1.1	.13865
	700	8.03	22.9	1.57	.17187
	800	9.93	29.79	2.28	.22158
	900	12.6	37.8	3.16	.27739
	1000	15.52	46.56	4.29	.34621

TABLE 3 contd.

PITCH	RRPM	LIFT BLADE	TOTAL LIFT. lb	H.P.	TORQUE lb.ft.
6°	300	2.44	7.32	.274	.06106
	400	4.36	13.00	.603	.11617
	500	6.74	20.22	1.08	.16978
	600	9.74	29.22	1.55	.20365
	700	13.91	39.5	2.31	.26487
	800	17.2	51.6	3.33	.33658
	900	21.8	65.4	4.89	.44539
8°	300	3.53	10.59	.425	.10506
	400	6.32	18.5	.725	.14817
	500	9.81	29.43	1.44	.2328
	600	14.51	42.45	2.23	.30365
10°	300	4.7	14.1	.581	.15106
	400	8.41	25.23	1.18	.24217
	500	13.05	39.15	2.06	.34078
	600	18.81	56.43	3.27	.45465
12°	300	5.9	17.7	.831	.22406
	600	23.6	70.8	4.91	.69465
14°	300	7.08	21.24	1.03	.28206

TABLE 4

PITCH	RRPM	LIFT BLADE	TOTAL LIFT.lb	H.P.	TORQUE lb.ft.
0°	300			0.175	.03306
	400			0.382	.06917
	500			0.68	.10078
	600			1.01	.12665
	700			1.6	.17887
	800			2.23	.22058
	900			3.22	.29039
	1000			4.38	. 3592
2°	300	0.42	1.68	0.183	.03506
	400	0.76	3.04	0.362	.06517
	500	1.18	4.72	0.647	.09517
	600	1.69	6.76	1.038	.13165
	700	2.44	9.35	1.608	.17987
	800	3.01	12.04	2.26	.22458
	900	3.82	15.28	3.17	.28539
	1000	4.7	18.8	4.46	.36621
4°	300	1.21	4.84	.228	.05273
	400	2.16	8.64	.483	.09217
	500	3.36	13.44	.855	.13277
	600	4.85	19.4	1.43	.18865
	700	6.94	26.5	2.12	.24487
	800	8.59	34.34	3.02	.30858
	900	10.8	43.2	4.4	.40739

TABLE 4 contd.

PITCH	RRPM	LIFT BLADE	TOTAL LIFT lb	H.P.	TORQUE lb.ft.
6°	300	2.16	8.64	0.357	.08706
	400	3.86	15.44	0.748	.15117
	500	5.98	23.92	1.33	.21778
	600	8.62	34.48	2.11	.28965
	700	12.98	47.5	3.22	.38487
	800	15.27	61.08	4.71	.49658
	900	19.40	77.6	6.92	.65639
8°	30	3.18	12.72	0.544	.14106
	400	5.68	22.72	1.05	.21417
	500	8.82	35.28	1.977	.33278
	600	12.7	50.8	3.23	.45565
10°	300	4.24	16.96	0.723	.19506
	400	7.59	30.36	1.47	.31217
	500	11.72	46.88	2.76	.47178
	600	16.95	67.8	4.69	.67165
	700	24.3	92.0	7.69	.95287
12°	300	5.98	23.92	1.405	.39706
	600	23.86	95.44	6.97	1.0076
14°	300	6.53	26.12	1.36	2.61106

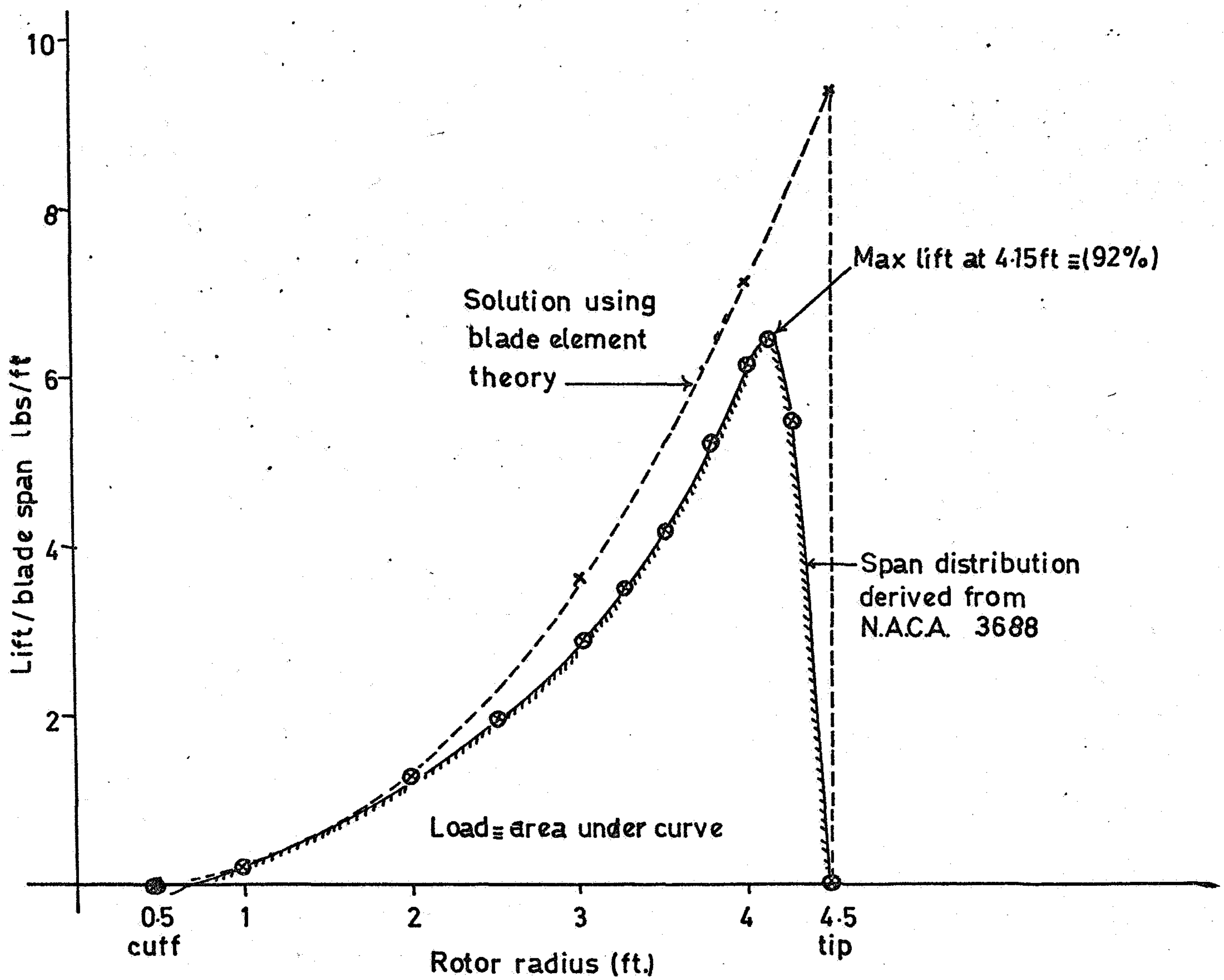


Fig.1 Comparison of spanwise loading calculated using blade element theory and estimated from N.A.C.A 3688 (method of obtaining empirical correction for calculating blade lift).

(Case illustrated: 3 blades - 6° pitch - 600 r.r.p.m.)

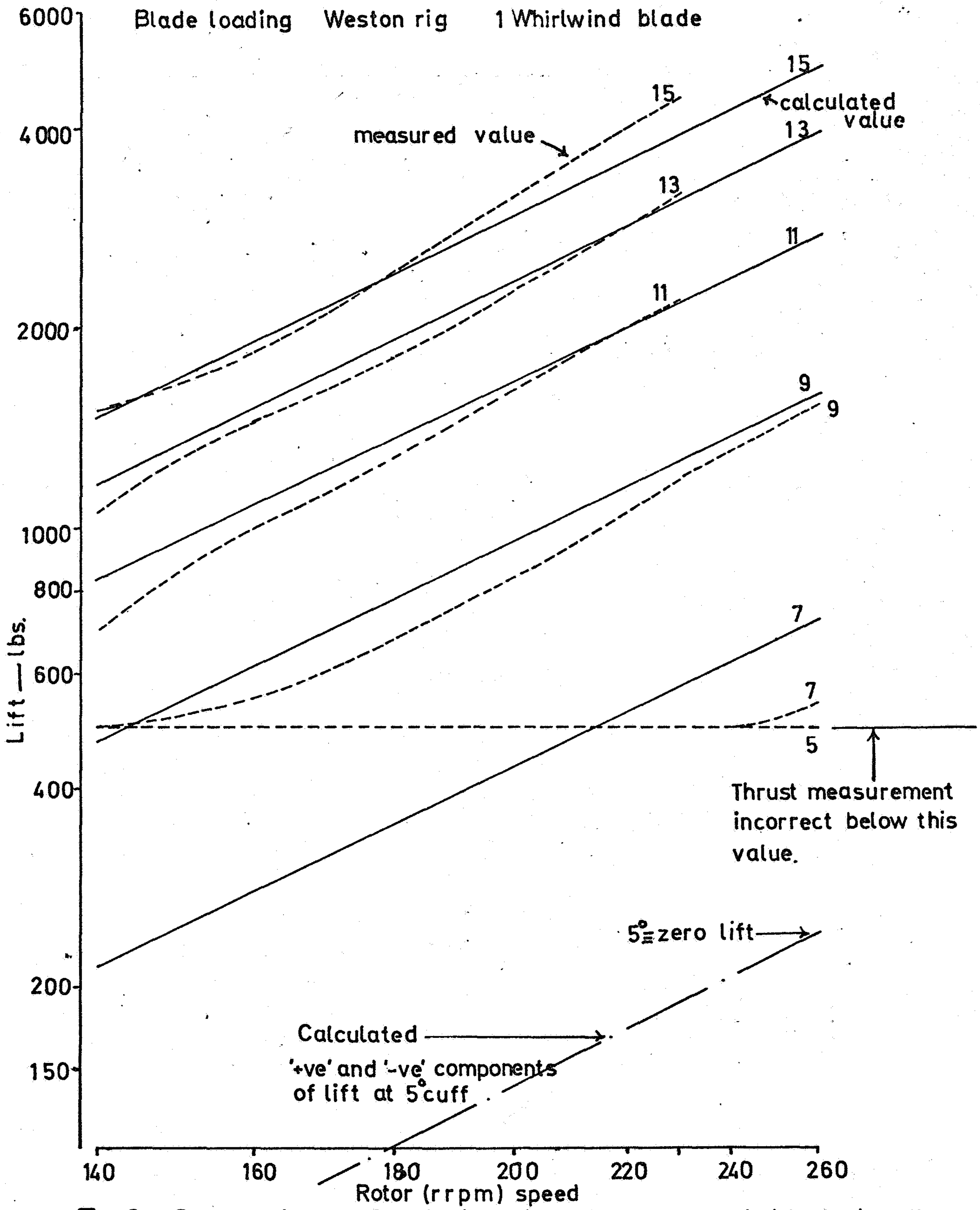


Fig. 2. Comparison of calculated and measured blade loading.

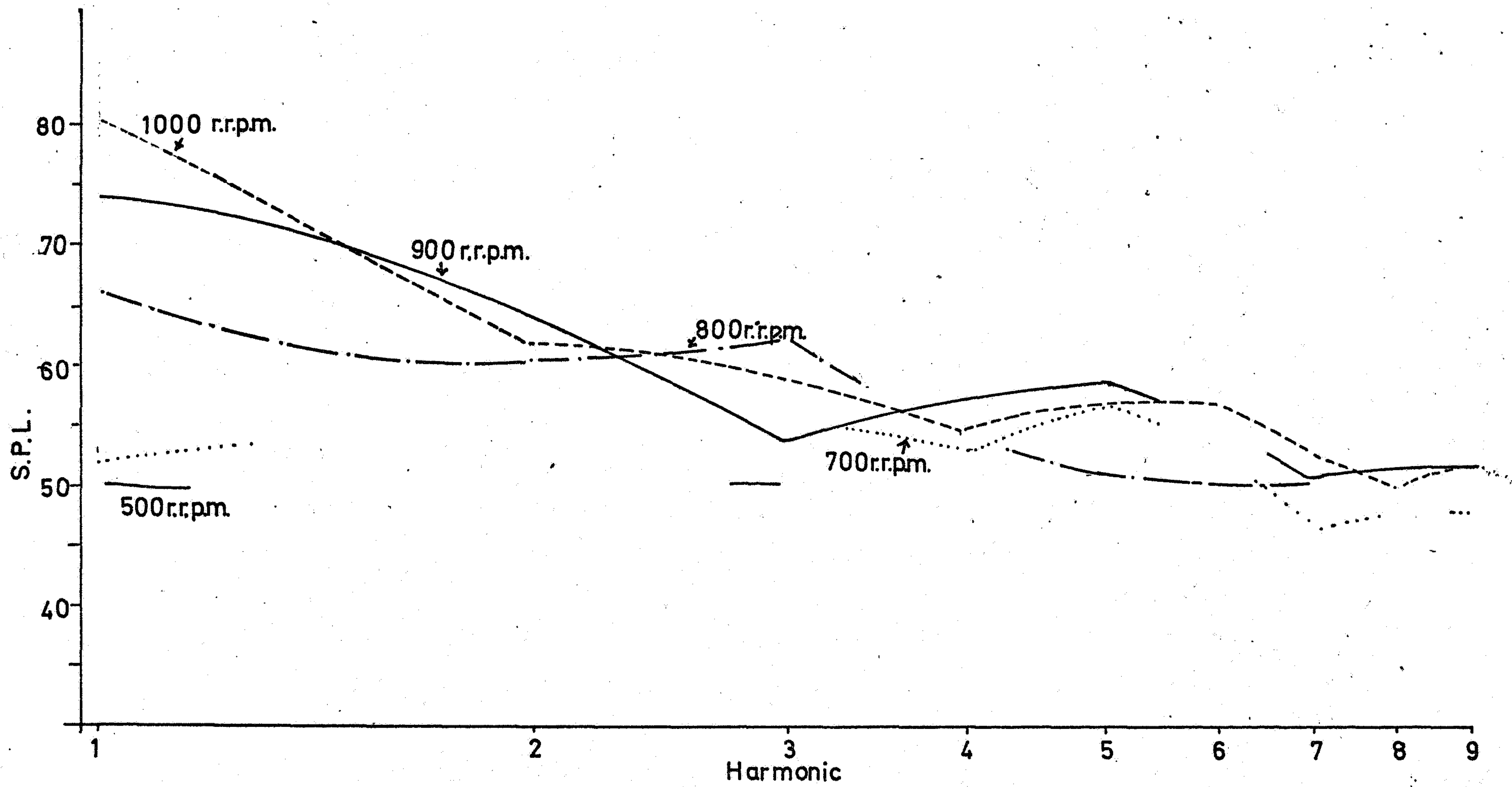


Fig.3. Effect of speed on spectrum shape at low pitch – 2° pitch – 3 blades

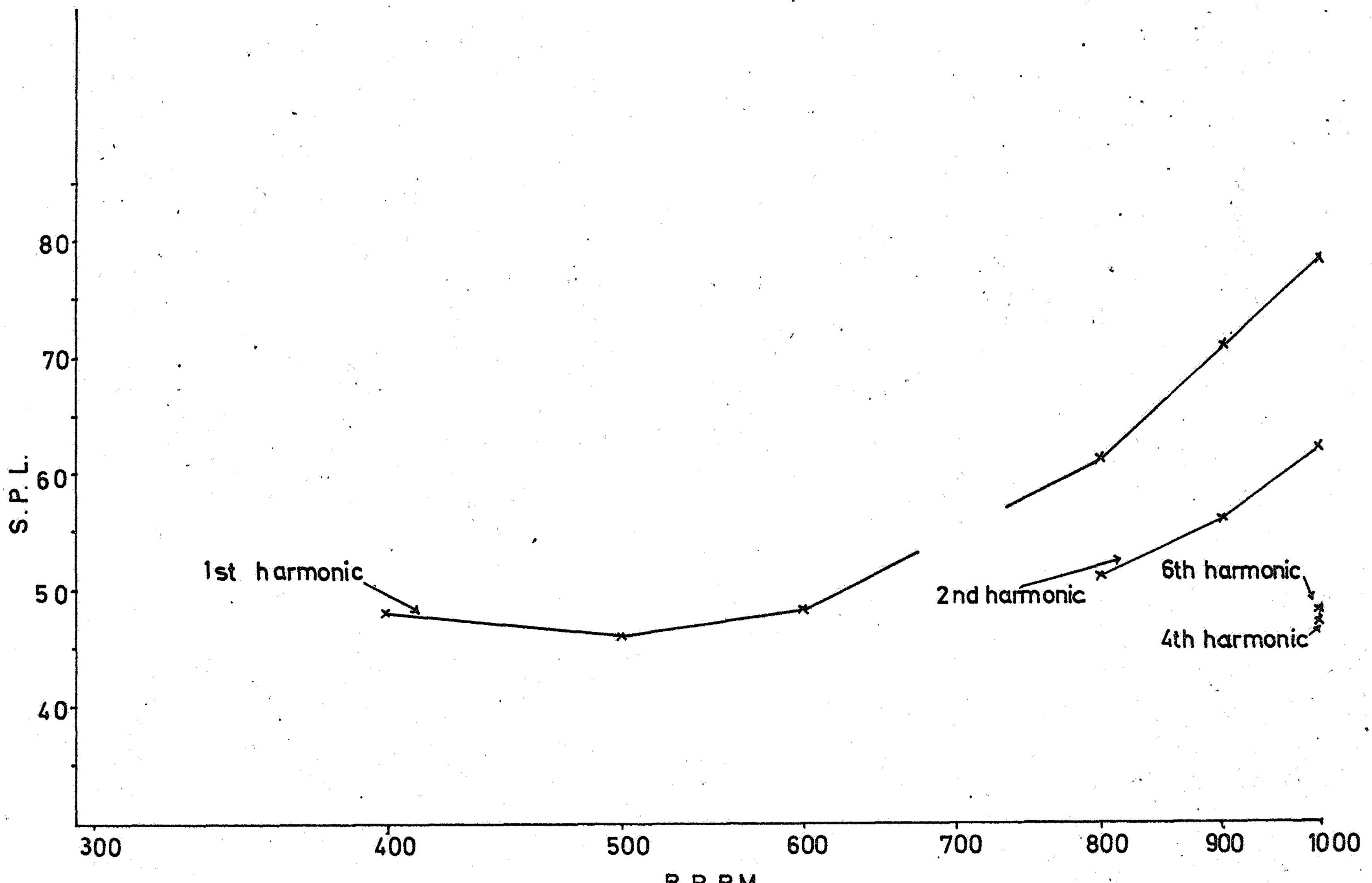


Fig.5. Zero pitch. S.R L. v Rotor speed.

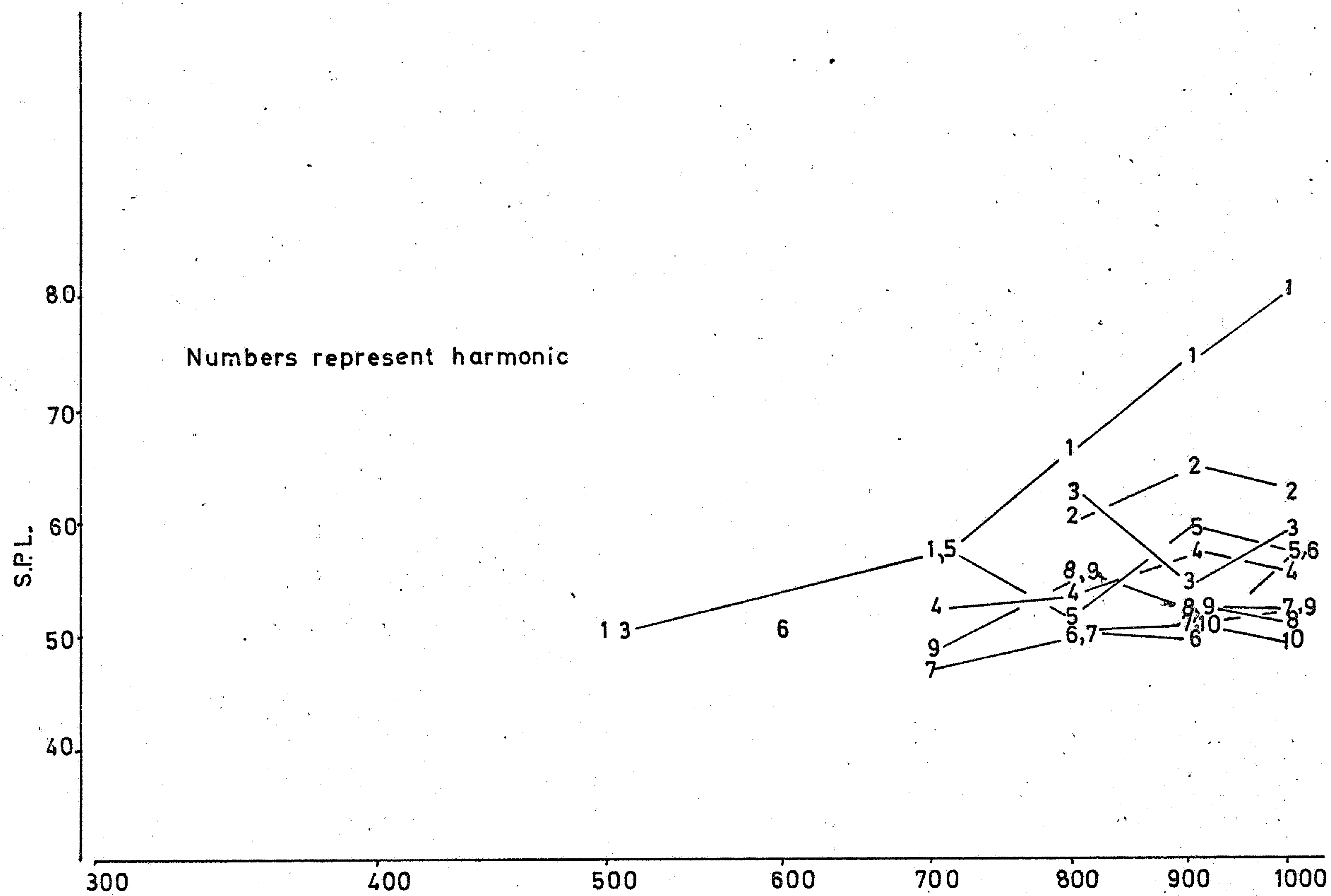


Fig. 5. 2° pitch
S.P.L.v Rotor speed

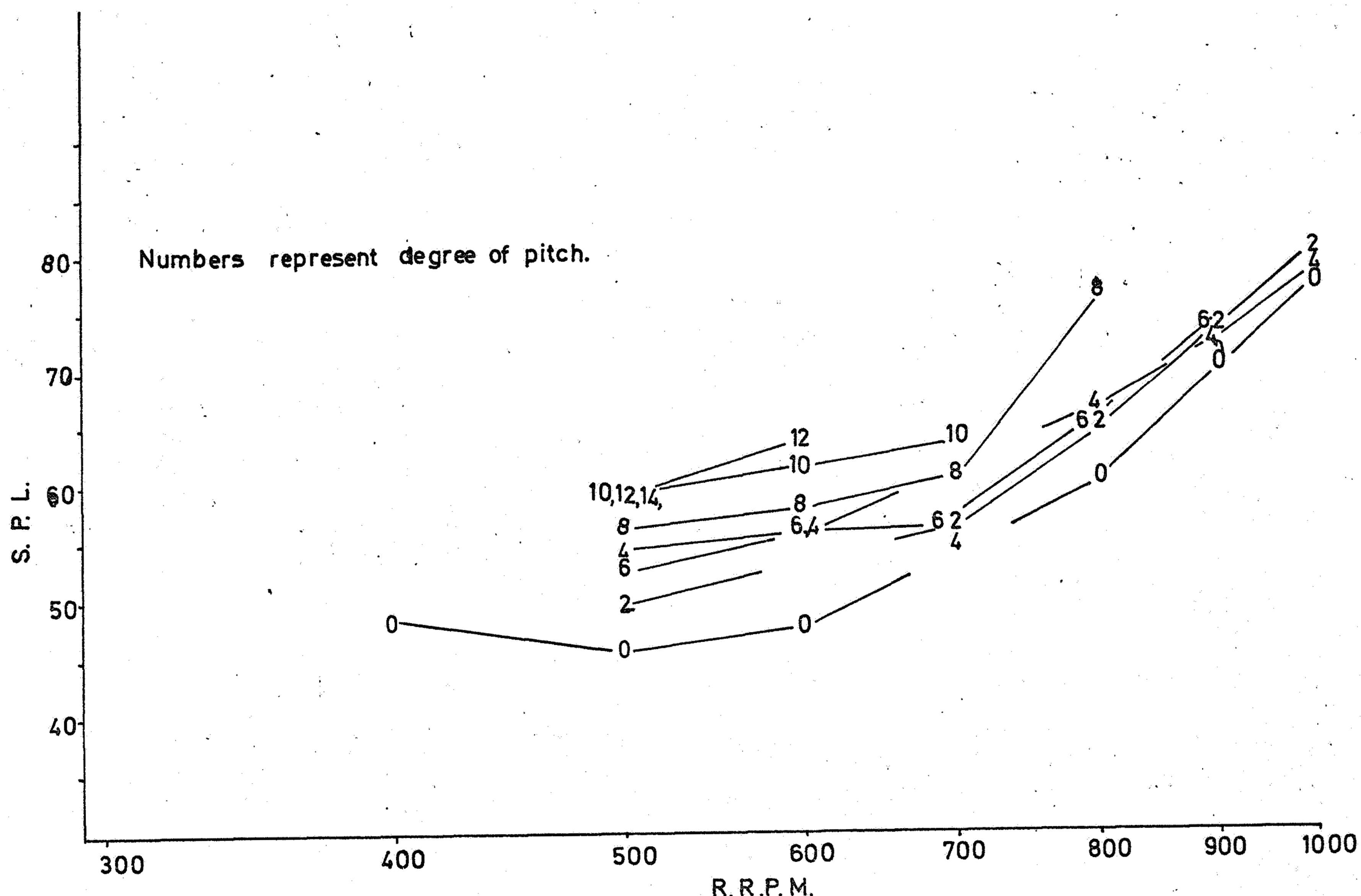


Fig. 6. 1st Harmonic S.P.L. v Rotor speed

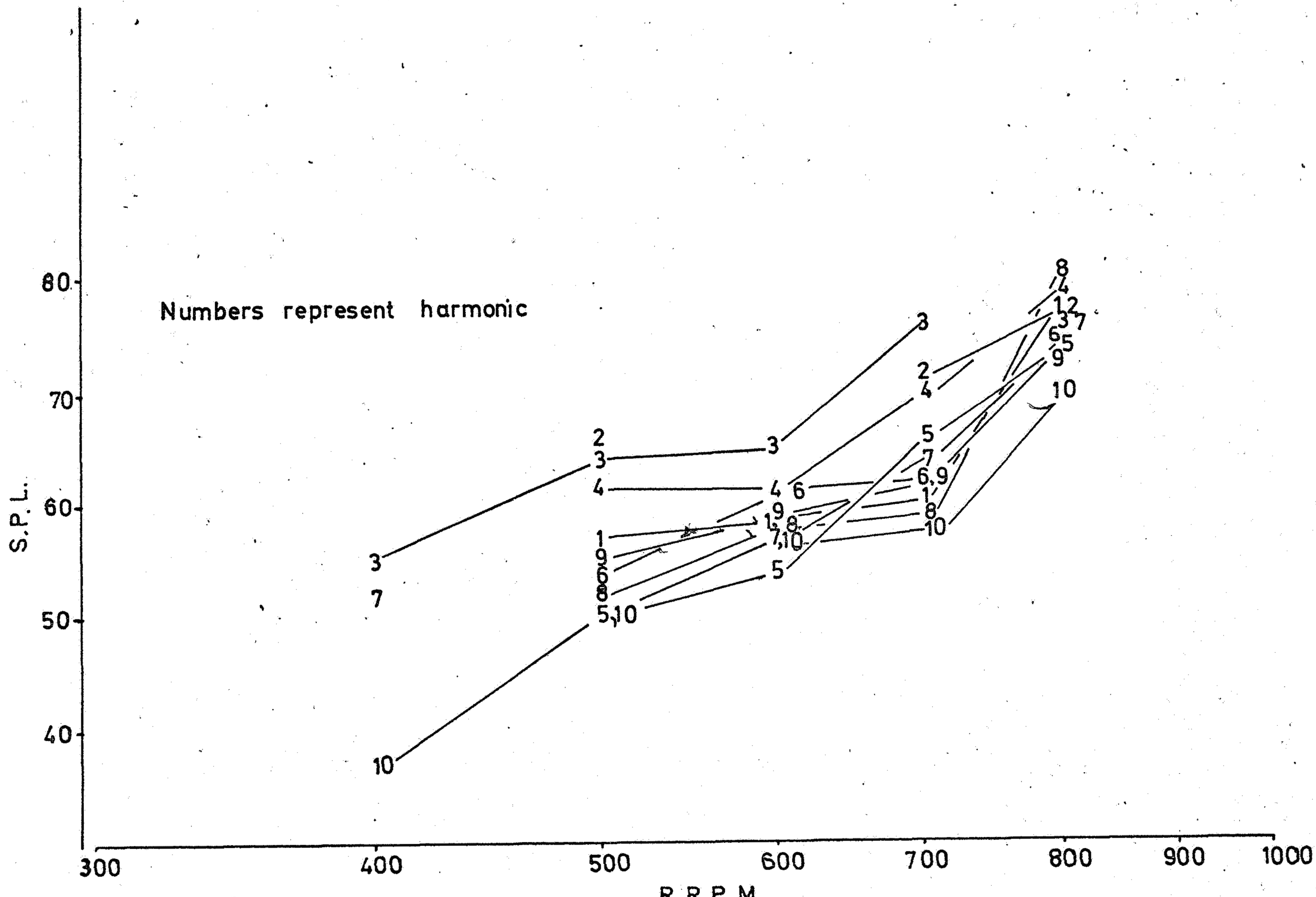
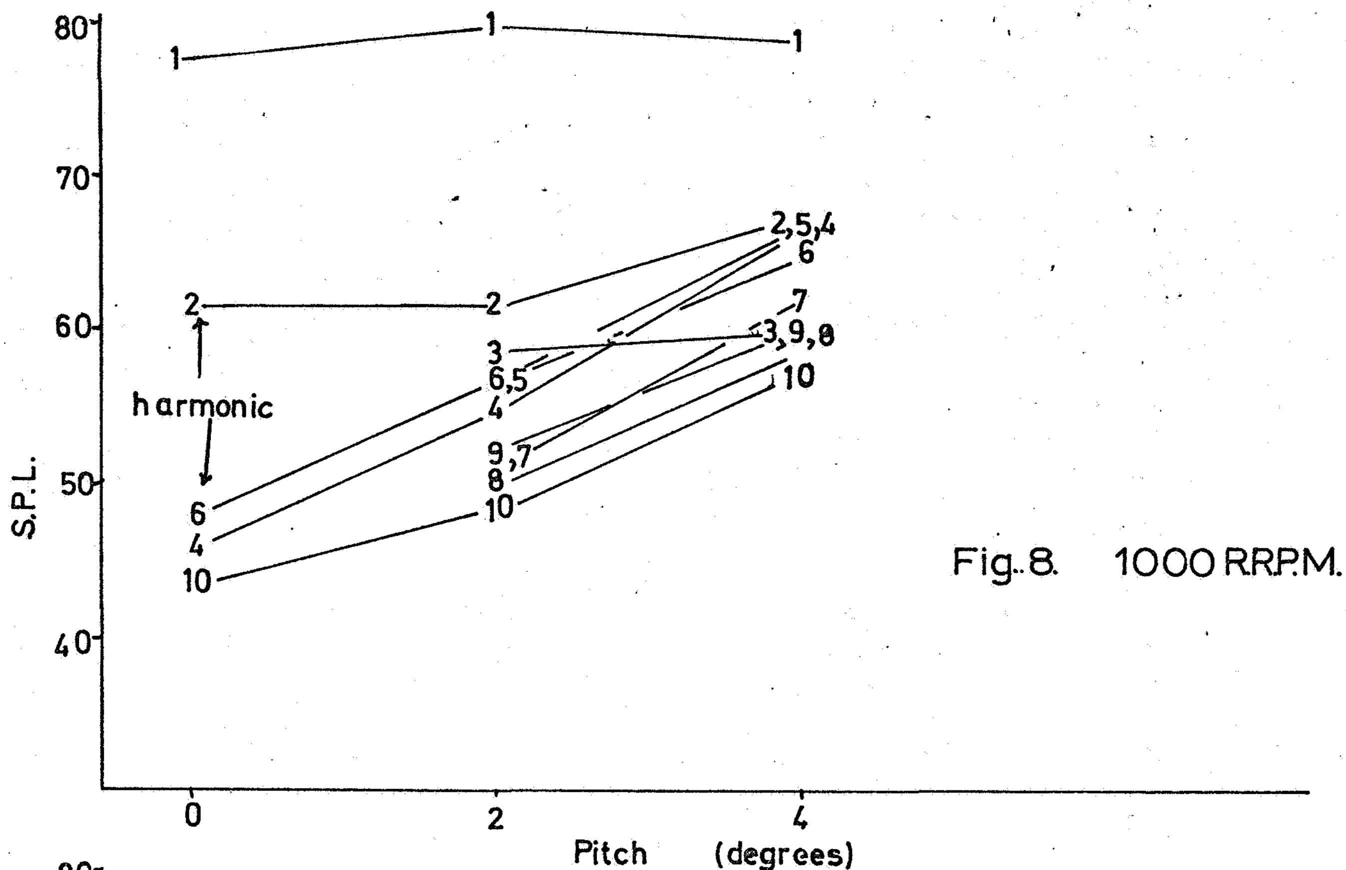


Fig. 7. 8° pitch
S.P.L.v Rotor speed.



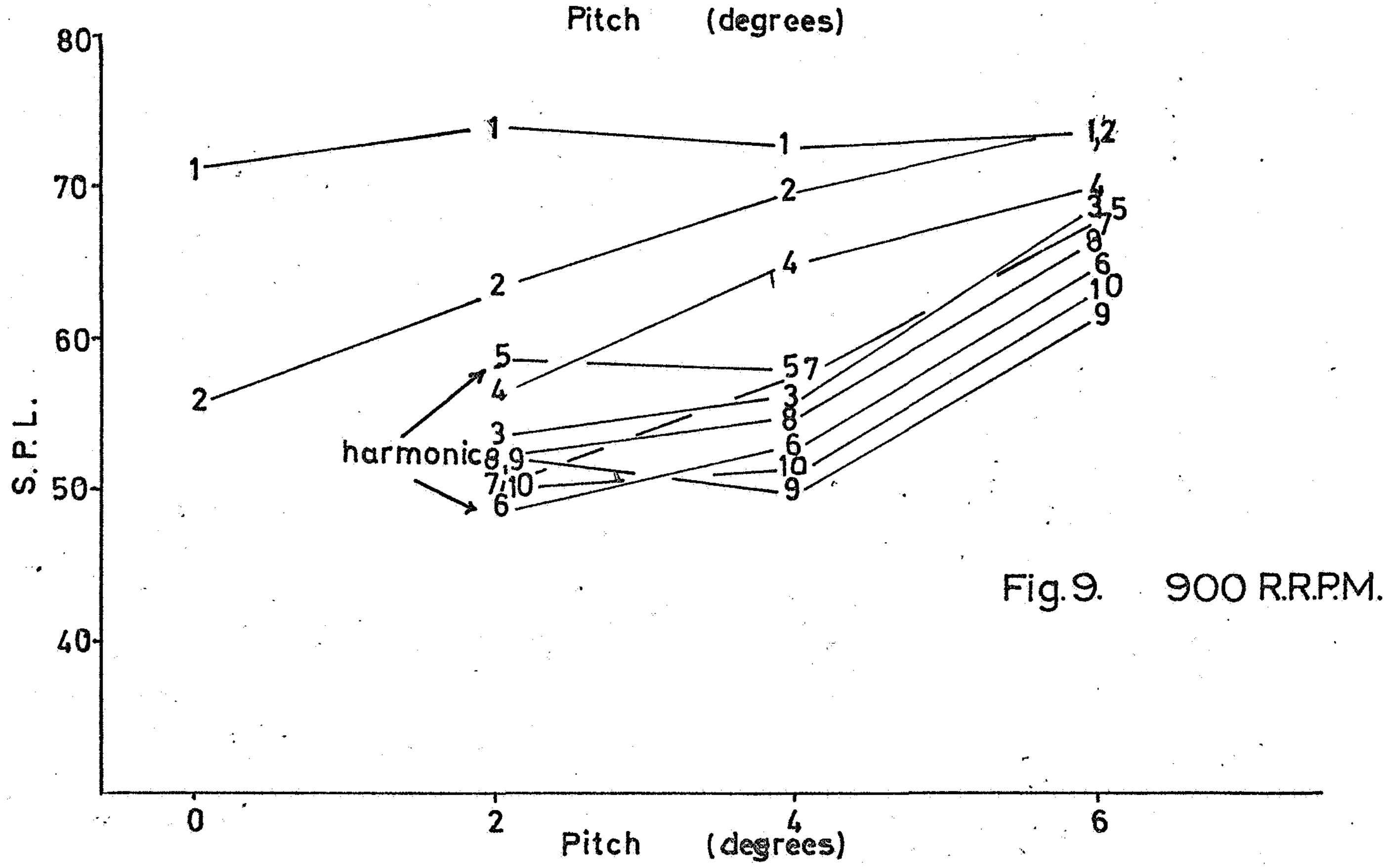


Fig. 8.&9. S.P.L. v Pitch

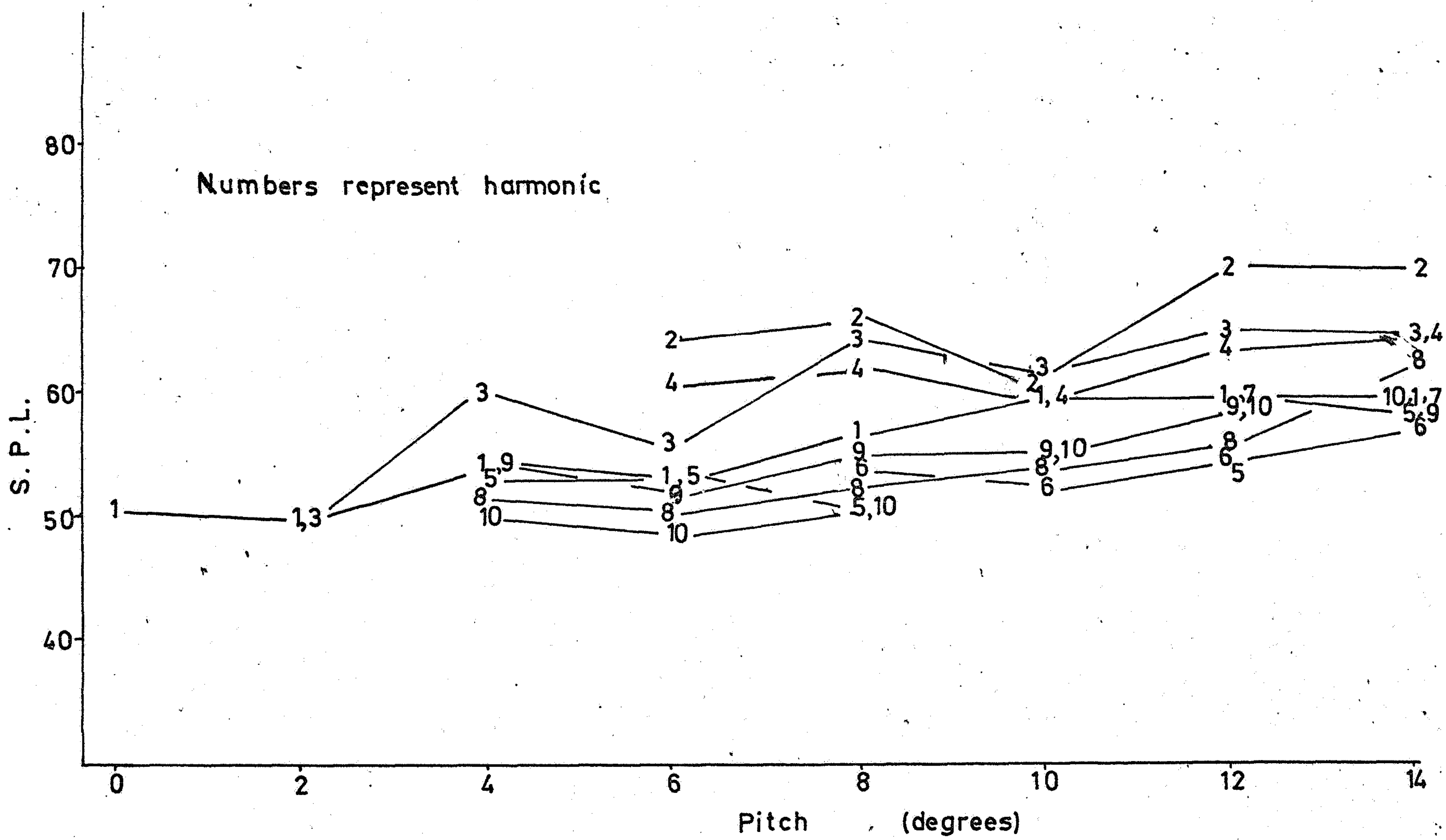


Fig. 10. 500 R.R.P.M. S.P.L. v Pitch

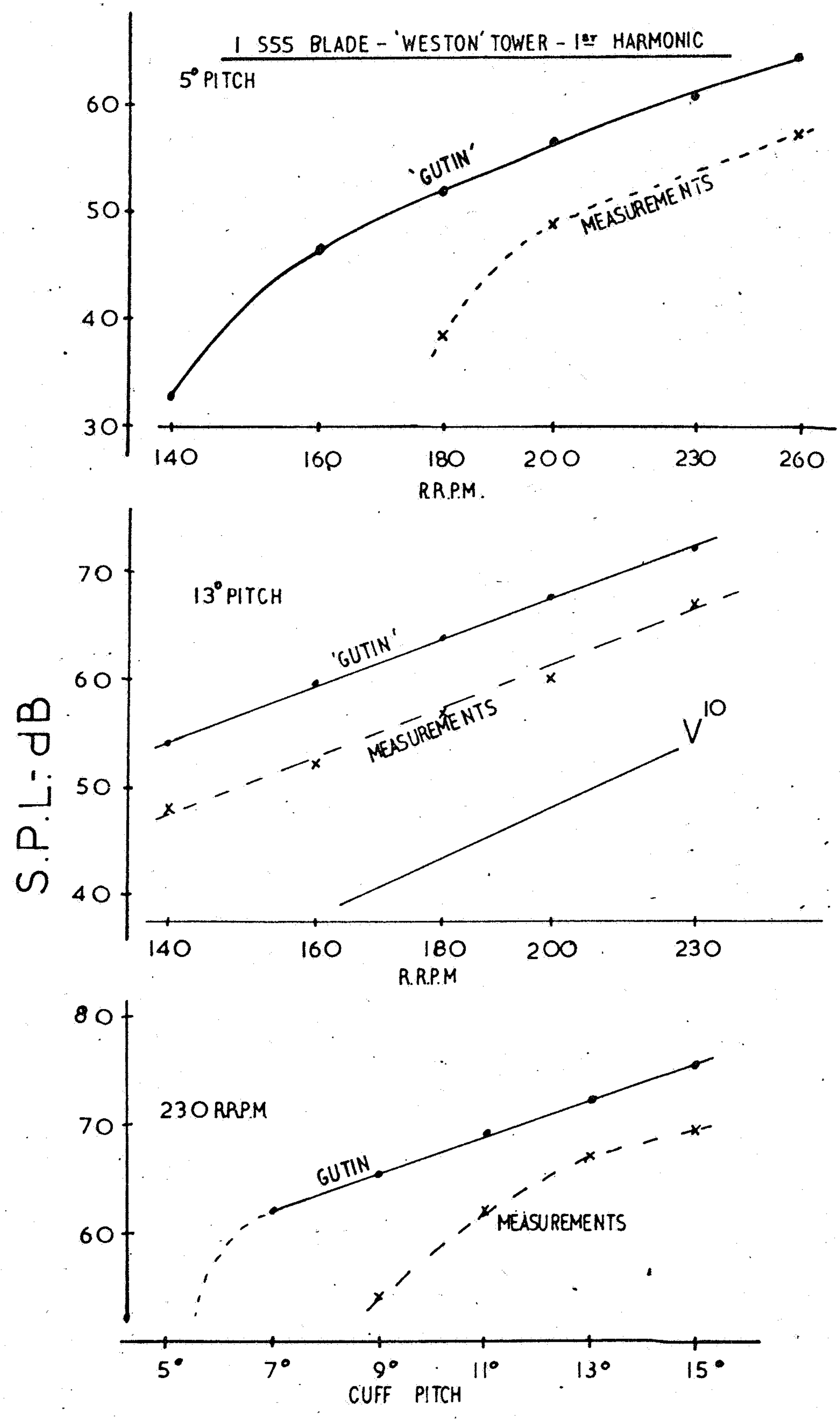


Fig.11. Full scale single bladed results.

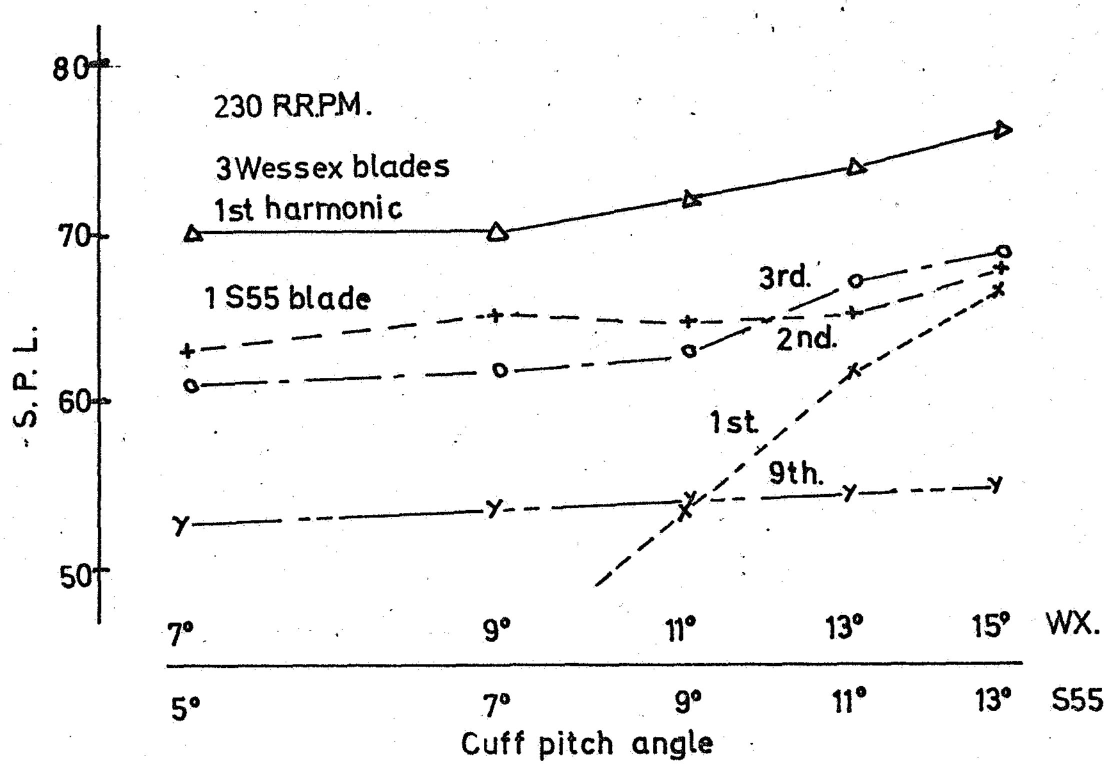


Fig.12. Rotational noise variation with pitch.

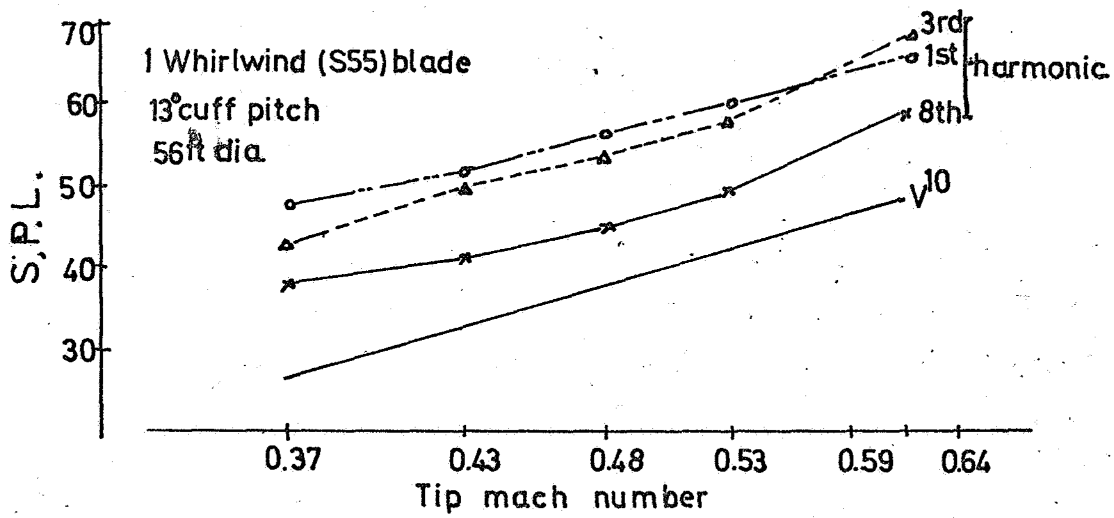


Fig.13. SPL v Tip mach number

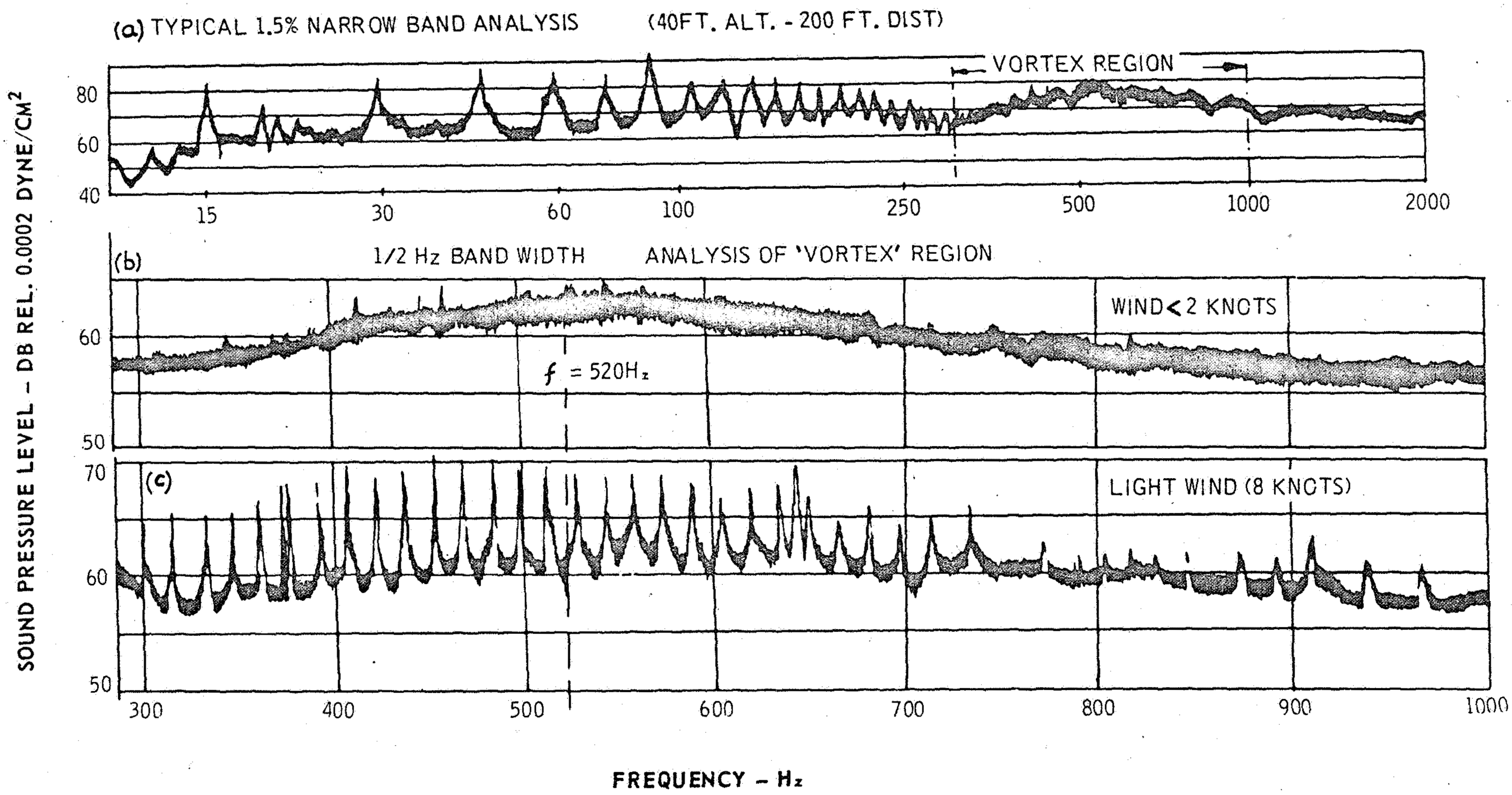


FIG. 14 NARROWBAND ANALYSIS OF HELICOPTER NOISE — HOVERING WESSEX.

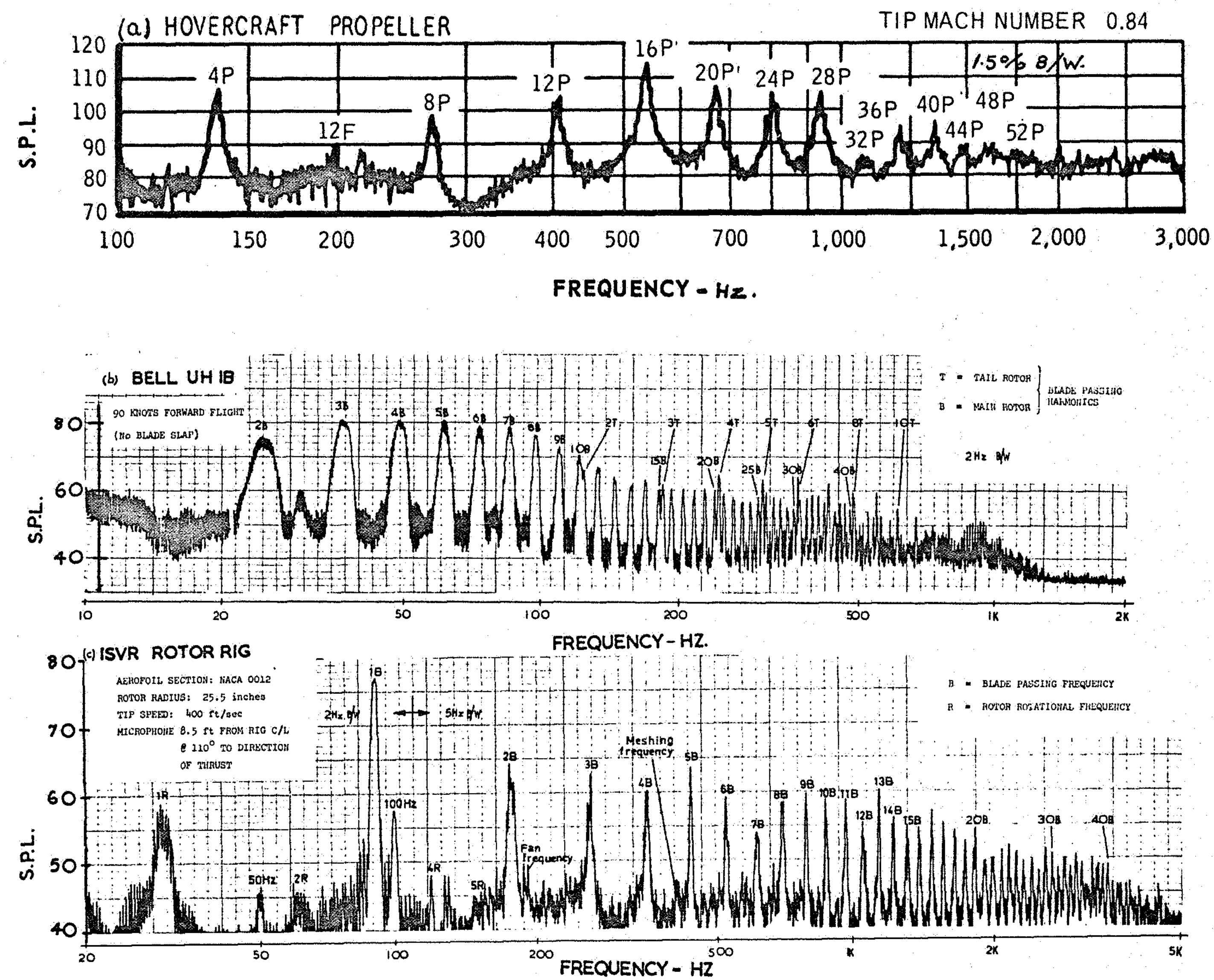


FIG.15 NARROWBAND ANALYSIS OF ROTOR NOISE

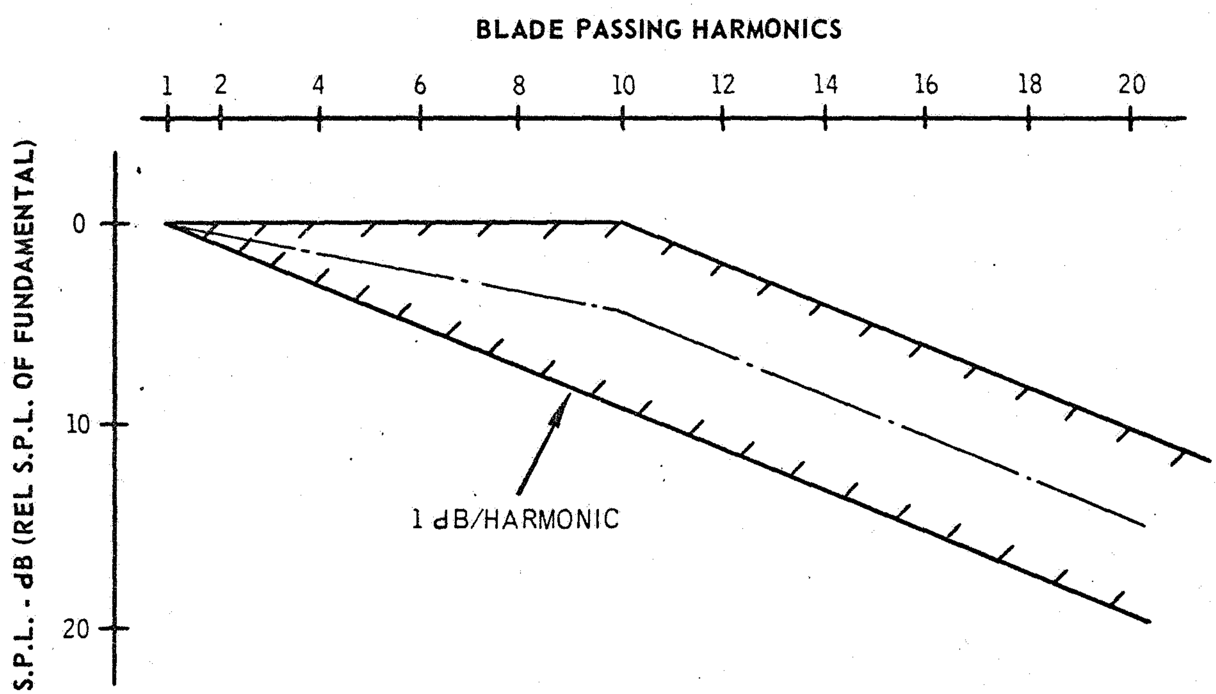


FIG.16. MAIN ROTOR ROTATIONAL NOISE – HARMONIC 'FALL OFF'