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**CASE FILE  
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A COMPUTATIONAL STUDY OF  
ROTATIONAL NOISE

By S.E. Wright and H.K. Tanna

I.S.V.R. Technical Report No. 15  
May, 1969.

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FACULTY OF ENGINEERING  
AND APPLIED SCIENCE

INSTITUTE OF SOUND AND VIBRATION RESEARCH

ACOUSTICS GROUP

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## PREFACE

The work reported here is a continuation of the investigation into the study of rotational noise reported earlier (I.S.V.R. Technical Report No. 5(1)). The purpose of this present report is to give in graphical form the computed output of an extensive computational study of rotational noise. No attempt however is made to interpret the output in any way or discuss its implications (see I.S.V.R. Technical Report No. 14 (2)).

The computation covers the properties of blade loading harmonic radiation for a wide range of rotor parameters, including near field, distributed loading both chord and span, and for tip speed in excess of Mach one. The investigation then considers composite blade loading radiation, both simple and compound. Finally the radiation is computed for an ensemble of blade loading harmonics corresponding to well-defined blade loading azimuth functions, similar to those produced by blade slap and rotor/stator interactions. The study although designed for a particular rotor (helicopter), has sufficient scope to cover geometries of other rotor configurations.

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## 1. Describing the computation

The investigation has been designed to establish the properties of rotational noise over as wide a range of parameters as computing time would allow. Bearing in mind that the typical computing time on a high speed computer is of the order of six seconds per harmonic per field point, then each computed case must be an attempt to achieve maximum information for minimum computing time. In some cases it would have been an advantage to increase the spectrum or polar resolution by at least a factor of two or have decreased the integration interval by at least the same margin, but of course the computing time and therefore the cost would have doubled.

### 1.1 Standard case

As a consequence of the number of parameters involved, a standard case has been adopted such that the sound pressure is calculated for a standard set of parameters (those of a typical helicopter rotor) and then deviations in radiation computed for a range of parameter changes taken one at a time; it is of course computationally prohibitive to cover all combinations of rotor variables. However, some parameter reduction is possible; for instance, the sound pressure harmonics ( $m$ ) are plotted in terms of the  $mB$  parameter, as  $m$  and  $B$  (blade number) are indistinguishable mathematically, even for distributive loading - e.g. if  $B = 4$  and  $m = 1$  or  $B = 1$  and  $m = 4$  the sound pressure level (S.P.L.) is the same. The spectrum envelope, both in shape and level is independent of the number of blades providing the total arithmetic blade loading is

the same. Only spectrum levels of  $mB$  numbers corresponding to multiples of  $B$  have physical significance. Similarly the rotor frequency ( $N$ ) and the effective radius loading point ( $r_e$ ) can be plotted in the form of an effective Mach number parameter ( $M_e$ ). The values for the standard case are given in fig. 3.1.

## 1.2 Computation programme

The computer programme used for the study computes the ordered sound pressure spectrum related to the blade passage frequency at any observation position, including the near field. Both steady and fluctuating lift radiations are calculated in the form of individual blade loading harmonic radiations. The programme has the facility to compute distributive spanwise loading, but is restricted to rectangular distributions in chord profile. Full details of the programme are given in I.S.V.R. Technical Report No. 13 (3).

## 2. Defining the output

### 2.1 Single blade loading harmonics

For the study of blade loading harmonic (B.L.H.) properties, the total lift  $L_{OT}$  on the rotor is kept constant at 12,000 lbs irrespective of the number of blades, by adjusting the lift per blade accordingly. By making the B.L.H. coefficient ( $\alpha_s$ ) equal to unity throughout, the total arithmetic B.L.H. amplitude  $L_{ST}$  is also maintained at 12,000 lbs, irrespective of the B.L.H. order  $s$  or blade number  $B$ .

Four of the parameters listed in the standard case are linear para-

meters, i.e. the S.P.L. is directly related to their value. The first two, total lift  $L_{OT}$  and B.L.H. coefficient  $\alpha_s$ , are directly proportional to the sound pressure and the remaining two, rotor radius  $r$  (providing the blade aspect ratio is constant) and far field observer distance  $R$  are inversely proportional to the sound pressure. Obviously there is no need to compute a range of these values. For example, to correct for a rotor having half the total thrust (-6 dB), a B.L.H. coefficient of a tenth (-20 dB), a rotor radius of one half having the same tip speed (+ 6 dB) and an observer a third of the distance (+ 10 dB), then a total of 10 dB will have to be subtracted from the general spectrum level. The remaining parameters are not simple multipliers, they affect the spectrum shape as well as the general level; these are the blade force angle  $\beta$ , effective tip Mach number  $M_e$ , span distribution, and chord width  $a$ . Therefore the effects of the above parameters are computed over a limited range of practical interest.

Further, the sound pressure spectrum is a function of observer elevation angle for single B.L.H. radiations and depends on both elevation and azimuth angles for composite B.L. radiations. It was therefore decided to define all output at one fixed point for mB spectra, i.e., azimuth angle  $\theta = 0^\circ$  (from tail) and elevation angle  $\sigma = -30^\circ$  (below rotor plane). Polar plots corresponding to the polar elevation and polar plan were then positioned so as to contain the above coordinates. The observer distance  $R$  in each case is 300 ft from the centre of the rotor (see fig. 3.2).

In the case of near field calculations, where the S.P.L. is not directly related to the observer distance, the additional effects of mB

number, span distribution, rotor speed and rotor radius are also computed. The various span distributions used in the investigation are defined in fig. 3.3, and are calculated for a total lift of 3000 lbs per blade.

## 2.2 Continuous B.L. Spectrums

The additional parameters for the flat B.L. spectrum study are defined as a continuous spectrum of B.L.H. from  $s = 1 \rightarrow 200$  with zero B.L.H. fall-off ( $\alpha_s = 1$  for all  $s$  values) and zero B.L.H. phase  $\phi_s = 0^\circ$ . For computational convenience, the B.L.H. amplitude  $L_s$  is kept constant at 3000 lbs per blade irrespective of the blade number used. This means that to correct for a standard total arithmetic B.L. amplitude  $L_{ST}$  of 12,000 lbs,  $20 \log(B/4)$  will have to be subtracted from the computed level, e.g. if the computational blade number  $B = 12$  then the correction is -10 dB.

The phase  $\phi_s$  of the B.L.H. for the random phase study, is achieved for

- (a) Random polarity, by assigning random polarity to the cosine B.L. component and making the sine component zero at each radial station, the polarities for a given harmonic being identical at each of these stations.
- (b) Random phase, as above but both sine and cosine components having random polarity.
- (c) Uncorrelated phase. Here both sine and cosine components have random polarity but with zero correlation between radial stations.

The 6 dB per octave B.L. spectrum is defined as a continuous B.L. spectrum with  $\alpha_s = 0.1$  for  $s = 1$ , and then progressive values of  $\alpha_s$  reducing at the rate of 6 dB per octave in  $s$ .

### 2.3 B.L. azimuth functions

The blade loading azimuth functions used in the study are illustrated in fig. 3.4. The standard B.L. function is a single rectangular excursion per blade revolution  $E = 1$ , having a load solidity  $\rho = 1\%$ , or an excursion width  $W$  of 1% of the effective disc solidity, i.e.  $\rho = W/2\pi r_e$ . The height of the function, or load change  $\Delta L$ , is 50 lbs per in or 1800 lbs per blade, which when expressed as a percentage of the standard steady load of 3000 lbs per blade, is 60%. A load change  $\Delta L$  of 1800 lbs per blade corresponds to a maximum blade loading amplitude  $L_s \text{ max}$  (at low  $s$  numbers for rectangular and half cosine functions and at medium  $s$  numbers for full sine function) of 1 lb per in or 36 lbs per blade.

For computing purposes, this particular value of  $L_s \text{ max} = 36$  lbs per blade is kept constant throughout the azimuth B.L. study. Therefore if the number of function excursions  $E$ , or the load solidity  $\rho$  is for example doubled, then the load change is effectively halved, and 6 dB would have to be added to the computed spectrum level to correct for a standard load change of 1800 lbs per blade.

As in the case for the flat B.L. study, the total arithmetic B.L. is that of one blade times the blade number used in the computation. Therefore, if a radiation spectrum is required for a blade number other than that used in the computation, then a subtraction of  $20 \log B/B_r$  dB will have to be made from the general spectrum level, where  $B$  is the computational blade number and  $B_r$  is the required blade number.

Two further parameters which effect the computed S.P.L. are the azimuth and span integration interval. These parameters are discussed

fully in I.S.V.R. Technical Report 13. It is sufficient to say here that the accuracy of the computation is a function of the integration intervals used, and for economic reasons, these intervals were adjusted to give a reasonable accuracy for a realistic computing time.

A summary of the computed output is given in the list of figures and each computed case is fully defined in the case schedule.

### 3. Case Schedule

KEY: FLD - FIELD; F/O - FALLOFF; NO - NUMBER; OBS - OBSERVER; DIST - DISTANCE;  
 ∫ - INTEGRATION; INT - INTERVAL; K - KILO; ELEVA - ELEVATION; CYC - CYCLIC.

| CASE NO. | STUDY   | PLOT   | BLH NO | RESO- LUTION | BLADE NO | MAX | CHORD INS | FORCE ANGLE | ROTOR SPEED R.P.M. | ROTOR RADIUS FT. | M <sup>e</sup> | SPAN DISTRI- BUTION | L <sup>ST</sup> | OBS. DIST. FT. | ∫INT Δψ |
|----------|---------|--------|--------|--------------|----------|-----|-----------|-------------|--------------------|------------------|----------------|---------------------|-----------------|----------------|---------|
| 101      | FAR FLD | mB F/O | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | RECT 10%            | 12K             | 300            | 20      |
| 102      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 111                | 30               | 0.25           | RECT 10%            | "               | "              | 20      |
| 103      | "       | "      | 0      |              | 4        | 60  | 16        | 60          | 333                | 30               | 0.75           | RECT 10%            | "               | "              | 0.50    |
| 103A     | "       | "      | 0      |              | 4        | 60  | 16        | 60          | 444                | 30               | 1.00           | RECT 10%            | "               | "              | 0.50    |
| 104      | "       | "      | 0      |              | 4        | 60  | 16        | 60          | 555                | 30               | 1.25           | RECT 10%            | "               | "              | 0.50    |
| 105      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | CONST               | "               | "              | 20      |
| 105A     | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | ZERO LIFT           | "               | "              | 20      |
| 106      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | RECT 0.3%           | "               | "              | 20      |
| 107      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | TRIANG              | "               | "              | 20      |
| 108      | "       | "      | 0      |              | 4        | 20  | 16        | 00          | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 20      |
| 109      | "       | "      | 0      |              | 4        | 20  | 16        | 240         | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 20      |
| 110      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 20      |
| 111      | "       | "      | 0      |              | 4        | 20  | 16        | 60          | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 20      |
| 112      | "       | "      | 0      |              | 4        | 20  | 64        | 60          | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 20      |
| 113      | "       | ELEVA  | 0      | 50           | 1        | 6   | 16        | 60          | 222                | 30               | 0.25           | RECT 10%            | "               | "              | 40      |
| 114      | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 111                | 30               | 0.75           | RECT 10%            | "               | "              | 40      |
| 115      | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 333                | 30               | 1.25           | RECT 10%            | "               | "              | 40      |
| 116      | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 555                | 30               | 0.5            | RECT 10%            | "               | "              | 40      |
| 116A     | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 222                | 30               | 0.5            | CONST               | "               | "              | 40      |
| 117      | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 222                | 30               | 0.5            | ZERO LIFT           | "               | "              | 40      |
| 118      | "       | "      | 0      | 50           | 1        | 6   | 16        | 60          | 222                | 30               | 0.5            | RECT 0.3%           | "               | "              | 40      |
| 119      | "       | "      | 0      | 50           | 1        | 6   | 16        | 00          | 222                | 30               | 0.5            | TRIANG              | "               | "              | 40      |
| 120      | "       | "      | 0      | 50           | 1        | 6   | 16        | 240         | 222                | 30               | 0.5            | RECT 10%            | "               | "              | 40      |

| CASE NO. | STUDY   | PLOT   | BLH NO. | RESO-<br>LUTION<br>S | BLADE<br>NO. | mB<br>MAX | CHORD<br>INS | FORCE<br>ANGLE<br>$\beta$ | ROTOR<br>SPEED<br>R.P.M. | ROTOR<br>RADIUS<br>FT. | M <sub>e</sub> | SPAN<br>DISTRIB-<br>UTION | L <sub>ST</sub> | OBS.<br>DIST.<br>FT. | $\int$ INT<br>$\Delta\psi$ |
|----------|---------|--------|---------|----------------------|--------------|-----------|--------------|---------------------------|--------------------------|------------------------|----------------|---------------------------|-----------------|----------------------|----------------------------|
| 121      | FAR FLD | mB F/O | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | 30                     | 0.5            | RECT 10%                  | 12K             | 300                  | 2°                         |
| 122      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 111                      | "                      | 0.25           | RECT 10%                  | "               | "                    | 2°                         |
| 123      | "       | "      | 12      |                      | 4            | 80        | 16           | 6°                        | 333                      | "                      | 0.75           | RECT 10%                  | "               | "                    | 0.5°                       |
| 123A     | "       | "      | 12      |                      | 4            | 80        | 16           | 6°                        | 444                      | "                      | 1.00           | RECT 10%                  | "               | "                    | 0.5°                       |
| 124      | "       | "      | 12      |                      | 4            | 80        | 16           | 6°                        | 555                      | "                      | 1.25           | RECT 10%                  | "               | "                    | 0.5°                       |
| 125      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | TRIANG                    | "               | "                    | 2°                         |
| 125A     | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | CONST                     | "               | "                    | 2°                         |
| 126      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | ZERO LIFT                 | "               | "                    | 2°                         |
| 127      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 0.3%                 | "               | "                    | 2°                         |
| 128      | "       | "      | 12      |                      | 4            | 44        | 16           | 0°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 2°                         |
| 219      | "       | "      | 12      |                      | 4            | 44        | 16           | 24°                       | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 2°                         |
| 130      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 2°                         |
| 131      | "       | "      | 12      |                      | 4            | 44        | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 2°                         |
| 132      | "       | ELEVA  | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 111                      | "                      | 0.25           | RECT 10%                  | "               | "                    | 4°                         |
| 133      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 333                      | "                      | 0.75           | RECT 10%                  | "               | "                    | 4°                         |
| 134      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 555                      | "                      | 1.25           | RECT 10%                  | "               | "                    | 4°                         |
| 135      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 222                      | "                      | 0.5            | CONST                     | "               | "                    | 4°                         |
| 136      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 222                      | "                      | 0.5            | ZERO LIFT                 | "               | "                    | 4°                         |
| 136A     | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 0.3%                 | "               | "                    | 4°                         |
| 137      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 222                      | "                      | 0.5            | TRIANG                    | "               | "                    | 4°                         |
| 138      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 0°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 4°                         |
| 139      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 24°                       | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 4°                         |
| 140      | "       | "      | 12      | 5°                   | 6            | 18        | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 4°                         |
| 141      | "       | mB F/O | 48      |                      | 4            | 120       | 16           | 6°                        | 111                      | "                      | 0.25           | RECT 10%                  | "               | "                    | 0.5°                       |
| 142      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 333                      | "                      | 0.75           | RECT 10%                  | "               | "                    | 0.5°                       |
| 143      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 555                      | "                      | 1.25           | RECT 10%                  | "               | "                    | 0.5°                       |
| 144      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 222                      | "                      | 0.5            | CONST                     | "               | "                    | 0.5°                       |
| 145      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 222                      | "                      | 0.5            | ZERO LIFT                 | "               | "                    | 0.5°                       |
| 145A     | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 0.3%                 | "               | "                    | 0.5°                       |
| 146      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 222                      | "                      | 0.5            | TRIANG                    | "               | "                    | 0.5°                       |
| 147      | "       | "      | 48      |                      | 4            | 120       | 16           | 6°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 0.5°                       |
| 148      | "       | "      | 48      |                      | 4            | 120       | 16           | 0°                        | 222                      | "                      | 0.5            | RECT 10%                  | "               | "                    | 0.5°                       |

| CASE NO. | STUDY    | PLOT     | BLH NO<br>S | RESO-<br>LUTION<br>$\Delta\theta, \Delta\sigma$ | BLADE NO.<br>$\Delta MB$ | MB MAX | CHORD INS | FORCE ANGLE<br>$\beta$ | ROTOR SPEED<br>R.P.M. | ROTOR RADIUS<br>FT. | $M_e$ | SPAN<br>DISTRI-<br>BUTION | $L_{ST}$ | OBS.<br>DIST.<br>FT. | $\int INT \Delta\psi$ |
|----------|----------|----------|-------------|-------------------------------------------------|--------------------------|--------|-----------|------------------------|-----------------------|---------------------|-------|---------------------------|----------|----------------------|-----------------------|
| 149      | FAR FLD  | mb F/O   | 48          |                                                 | 4                        | 120    | 16        | $24^\circ$             | 222                   | 30                  | 0.5   | RECT 10%                  | 12K      | 300                  | $0.5^\circ$           |
| 150      | "        | "        | 48          |                                                 | 4                        | 120    | 1         | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $0.5^\circ$           |
| 151      | "        | "        | 48          |                                                 | 4                        | 120    | 64        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $0.5^\circ$           |
| 152      | "        | ELEVA    | 48          | $5^\circ$                                       | 4                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.25  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 153      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 111                   | "                   | 0.75  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 154      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 333                   | "                   | 1.25  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 155      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 555                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 156      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | CONST                     | "        | "                    | $2^\circ$             |
| 156A     | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | ZERO LIFT                 | "        | "                    | $2^\circ$             |
| 157      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 0.3%                 | "        | "                    | $2^\circ$             |
| 158      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | TRIANG                    | "        | "                    | $2^\circ$             |
| 159      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 160      | "        | "        | 48          | $5^\circ$                                       | 6                        | 54     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 161      | NEAR FLD | mb F/O   | 0           |                                                 | 4                        | 24     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | 15-300               | $2^\circ$             |
| 161A     | "        | "        | 12          |                                                 | 6                        | 24     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 161B     | "        | "        | 48          |                                                 | 24                       | 96     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $0.5^\circ$           |
| 162      | "        | ELEVA    | 0           | $10^\circ$                                      | 4                        | 4      | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | 15-240               | $6^\circ$             |
| 162A     | "        | "        | 12          | $10^\circ$                                      | 6                        | 18     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 162B     | "        | "        | 12          | $10^\circ$                                      | 6                        | 18     | 16        | $6^\circ$              | 222                   | "                   | 0.5   | RECT 10%                  | "        | "                    | $2^\circ$             |
| 163      | "        | OBS DIST | 0           |                                                 | 4                        | 4      | 16        | $6^\circ$              | 111                   | "                   | 0.25  | RECT 10%                  | "        | 22-300               | $6^\circ$             |
| 163A     | "        | "        | 12          |                                                 | 6                        | 18     | 16        | $6^\circ$              | 111                   | "                   | 0.25  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 164      | "        | "        | 0           |                                                 | 4                        | 4      | 16        | $6^\circ$              | 333                   | "                   | 0.75  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 164A     | "        | "        | 12          |                                                 | 6                        | 18     | 16        | $6^\circ$              | 333                   | "                   | 0.75  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 165      | "        | "        | 0           |                                                 | 4                        | 4      | 16        | $6^\circ$              | 444                   | "                   | 1.00  | RECT 10%                  | "        | "                    | $6^\circ$             |
| 165A     | "        | "        | 12          |                                                 | 6                        | 18     | 16        | $6^\circ$              | 444                   | "                   | 1.00  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 166      | "        | "        | 0           |                                                 | 4                        | 4      | 16        | $6^\circ$              | 555                   | "                   | 1.25  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 166A     | "        | "        | 12          |                                                 | 6                        | 18     | 16        | $6^\circ$              | 555                   | "                   | 1.25  | RECT 10%                  | "        | "                    | $2^\circ$             |
| 167      | "        | "        | 0           |                                                 | 4                        | 4      | 5.33      | $6^\circ$              | 222                   | 10                  | 0.167 | RECT 10%                  | "        | 5-100                | $6^\circ$             |
| 167A     | "        | "        | 12          |                                                 | 6                        | 18     | 5.33      | $6^\circ$              | 222                   | 10                  | 0.167 | RECT 10%                  | "        | "                    | $2^\circ$             |
| 168      | "        | "        | 0           |                                                 | 4                        | 4      | 1.6       | $6^\circ$              | 222                   | 3                   | 0.05  | RECT 10%                  | "        | 1.5-30               | $6^\circ$             |

| CASE NO. | STUDY     | PLOT      | B.L.H. NO.<br>S | RESOLUTION<br>$\Delta\theta, \Delta\sigma$ | BLADE NO.<br>$\Delta mB$ | mB MAX | CHORD INS | FORCE ANGLE<br>$\beta$ | R.P.M. | ROTOR RADIUS<br>FT. | $M_e$ | SPAN<br>DISTRIBUTION | $L_{ST}$    | OBS DIST<br>FT. | $\int INT \Delta\psi$ |
|----------|-----------|-----------|-----------------|--------------------------------------------|--------------------------|--------|-----------|------------------------|--------|---------------------|-------|----------------------|-------------|-----------------|-----------------------|
| 168A     | NEAR FLD  | OBS.DIST. | 12              |                                            | 6                        | 18     | 1.6       | 6°                     | 222    | 3                   | 0.05  | RECT 10%             | 12K         | 1.5             | 2°                    |
| 169      | "         | "         | 0               |                                            | 4                        | 4      | 0.533     | "                      | "      | 1                   | 0.017 | "                    | "           | 0.5             | 6°                    |
| 169A     | "         | "         | 12              |                                            | 6                        | 18     | "         | "                      | "      | 1                   | 0.017 | "                    | "           | "               | 2°                    |
| 170      | "         | "         | 0               |                                            | 4                        | 4      | 16        | "                      | "      | 30                  | 0.5   | "                    | "           | 12              | 6°                    |
| 171      | "         | "         | 0               |                                            | 4                        | 4      | "         | "                      | "      | "                   | "     | RECT 0.3%            | "           | "               | "                     |
| 172      | "         | "         | 0               |                                            | 4                        | 4      | "         | "                      | "      | "                   | "     | CONST                | "           | "               | "                     |
| 173      | "         | "         | 0               |                                            | 4                        | 4      | "         | "                      | "      | "                   | "     | TRIANG               | "           | "               | "                     |
| 174      | SIM.ADD   | mB F/O    | 24              |                                            | 4                        | 48     | "         | "                      | "      | "                   | "     | RECT 10%             | "           | 300             | 1°                    |
| 175      | "         | "         | 12+24           |                                            | 4                        | 48     | "         | "                      | "      | "                   | "     | "                    | "           | "               | 1°                    |
| 176      | "         | ELEV.PLAN | 12              | 10°, 10°                                   | 24                       | 24     | "         | "                      | "      | "                   | "     | "                    | 72K         | "               | 2°                    |
| 177      | "         | ELEVATION | 24              | 10°                                        | 24                       | 24     | "         | "                      | "      | "                   | "     | "                    | 72K         | "               | 2°                    |
| 178      | "         | ELEV.PLAN | 12+24           | 10°, 10°                                   | 24                       | 24     | "         | "                      | "      | "                   | "     | "                    | 72K         | "               | 2°                    |
| 179      | CONT.SPEC | mB F/O    | 1+100           |                                            | 6                        | 96     | "         | "                      | "      | "                   | "     | "                    | 18K         | "               | 0.5°                  |
| 179A     | "         | "         | 1+100           |                                            | 10                       | 250    | "         | "                      | "      | "                   | "     | "                    | 30K         | "               | "                     |
| 179B     | "         | "         | 1+100           |                                            | 4                        | 100    | 64        | "                      | "      | "                   | "     | "                    | 12K         | "               | "                     |
| 180      | "         | "         | 1+100           |                                            | 6                        | 96     | 16        | "                      | "      | "                   | "     | "                    | 18K         | "               | "                     |
| 181      | "         | "         | 1+100           |                                            | 6                        | 66     | "         | "                      | "      | "                   | "     | "                    | 18K         | "               | "                     |
| 182      | "         | "         | 1+100           |                                            | 6                        | 66     | "         | "                      | "      | "                   | "     | "                    | -           | "               | "                     |
| 182A     | "         | "         | 1+100           |                                            | 2                        | 24     | "         | "                      | "      | "                   | "     | "                    | -           | "               | 1°                    |
| 183      | "         | ELEV.PLAN | 1+100           | 20°, 20°                                   | 12                       | 48     | "         | "                      | "      | "                   | "     | "                    | 36K         | "               | 0.5°                  |
| 184      | "         | "         | 1+100           | 20°, 20°                                   | 12                       | 48     | "         | "                      | "      | "                   | "     | "                    | 36K         | "               | 1°                    |
| 185      | "         | "         | 1+100           | 20°, 20°                                   | 12                       | 48     | "         | "                      | "      | "                   | "     | "                    | 36K         | "               | 1°                    |
| 186      | "         | "         | "               | 20°, 20°                                   | 12                       | 48     | "         | "                      | "      | "                   | "     | "                    | -           | "               | 1°                    |
| 187      | AZM.FN.   | mB F/O    | "               |                                            | 6                        | 96     | "         | "                      | "      | "                   | "     | "                    | $\rho=1\%$  | "               | 0.5°                  |
| 187A     | "         | "         | "               |                                            | 1                        | 99     | "         | "                      | "      | "                   | "     | "                    | $\rho=1\%$  | "               | "                     |
| 188      | "         | "         | "               |                                            | 6                        | 96     | "         | "                      | "      | "                   | "     | "                    | $\rho=10\%$ | "               | "                     |
| 188A     | "         | "         | "               |                                            | 1                        | 99     | "         | "                      | "      | "                   | "     | "                    | $\rho=10\%$ | "               | "                     |
| 189      | "         | "         | "               |                                            | 6                        | 96     | "         | "                      | "      | "                   | "     | "                    | $\rho=50\%$ | "               | "                     |
| 189A     | "         | "         | "               |                                            | 1                        | 99     | "         | "                      | "      | "                   | "     | "                    | $\rho=50\%$ | "               | "                     |
| 190      | "         | "         | "               |                                            | 6                        | 96     | "         | "                      | "      | "                   | "     | "                    | $E=4$       | "               | "                     |
| 190A     | "         | "         | "               |                                            | 1                        | 99     | "         | "                      | "      | "                   | "     | "                    | $E=4$       | "               | "                     |

| CASE NO. | STUDY      | PLOT      | B.L.H. NO. S | RESOLUTION $\Delta\theta, \Delta\sigma$ | BLADE NO. $\Delta mB$ | mB MAX | CHORD INS | FORCE ANGLE $\beta$ | ROTOR SPEED R.P.M. | ROTOR RADIUS FT. | M <sub>e</sub> | SPAN DISTRIBUTION | L <sub>ST</sub> | OBS DIST. FT. | $\int INT \Delta\psi$ |
|----------|------------|-----------|--------------|-----------------------------------------|-----------------------|--------|-----------|---------------------|--------------------|------------------|----------------|-------------------|-----------------|---------------|-----------------------|
| 191      | AZM. FN.   | mB F/O    | 1-100        |                                         | 6                     | 96     | 16        | 6°                  | 222                | 30               | 0.5            | RECT 10%          | E=16            | 300           | 0.5°                  |
| 191A     | "          | "         | "            |                                         | 1                     | 99     | "         | "                   | "                  | "                | "              | "                 | E=16            | "             | 0.5°                  |
| 192      | "          | ELEV PLAN | "            | 10°, 10°                                | 12                    | 48     | "         | "                   | "                  | "                | "              | "                 | $\rho=1\%$      | "             | 1°                    |
| 193      | "          | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "              | "                 | $\rho=10\%$     | "             | "                     |
| 194      | "          | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "              | "                 | $\rho=50\%$     | "             | "                     |
| 195      | "          | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "              | "                 | E=4             | "             | "                     |
| 196      | "          | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "              | "                 | E=16            | "             | "                     |
| 201      | FLAT SPEC. | mB F/O    | 1-200        |                                         | 2                     | 10     | "         | "                   | "                  | "                | "              | "                 | "               | "             | 0.5°                  |
| 202      | "          | "         | "            |                                         | 2                     | 10     | "         | "                   | "                  | "                | "              | "                 | 6K              | "             | 1°                    |
| 203      | "          | "         | "            |                                         | 10                    | 420    | "         | "                   | "                  | "                | "              | "                 | 30K             | "             | 0.5°                  |
| 204      | "          | "         | "            |                                         | 10                    | 420    | "         | "                   | "                  | "                | "              | "                 | 30K             | "             | 1°                    |
| 205      | CONT SPEC  | "         | 1-100        |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | 18K             | "             | 0.5°                  |
| 206      | "          | ELEVATION | "            | 10°                                     | 12                    | 48     | "         | "                   | "                  | "                | "              | "                 | 36K             | "             | 1°                    |
| 207      | FLAT SPEC  | mB F/O    | 1-200        |                                         | 10                    | 450    | "         | "                   | "                  | "                | "              | "                 | 30K             | "             | 0.25°                 |
| 208      | NEAR FLD   | mB F/O    | 0-50         |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | 18K             | 30            | 2°                    |
| 209      | "          | "         | "            |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | "               | 30            | 1°                    |
| 210      | "          | "         | "            |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | "               | 30            | 0.5°                  |
| 211      | "          | "         | "            |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | "               | 30            | 0.25°                 |
| 212      | CYC PITCH  | "         | 1-50         |                                         | 6                     | 96     | "         | "                   | "                  | "                | "              | "                 | "               | 300           | 0.5                   |
| 212A     | "          | "         | 0            |                                         | 4                     | 24     | "         | "                   | "                  | "                | "              | "                 | 12K             | "             | "                     |
| 213      | "          | "         | 1-50         |                                         | 6                     | 96     | "         | 6°+CYC              | "                  | "                | "              | "                 | 18K             | "             | "                     |
| 213A     | "          | "         | 0            |                                         | 4                     | 24     | "         | "                   | "                  | "                | "              | "                 | 12K             | "             | "                     |
| 214      | "          | "         | 1-50         |                                         | 6                     | 96     | "         | CYC                 | "                  | "                | "              | "                 | 18K             | "             | "                     |
| 214A     | "          | "         | 0            |                                         | 4                     | 24     | "         | "                   | "                  | "                | "              | "                 | 12K             | "             | "                     |
| 215      | FLAT SPEC  | mB F/O    | 1-200        |                                         | 12                    | 240    | "         | 6°                  | "                  | "                | "              | "                 | 36K             | 30-300        | "                     |
| 215A     | "          | "         | "            |                                         | 2                     | 24     | "         | "                   | "                  | "                | "              | "                 | 6K              | 300           | 1°                    |
| 215B     | "          | "         | "            |                                         | 12                    | 240    | "         | "                   | "                  | "                | "              | "                 | 36K             | "             | 0.5°                  |
| 216      | "          | "         | "            |                                         | 12                    | 240    | "         | "                   | 111                | "                | "              | "                 | "               | "             | 0.25°                 |
| 216A     | "          | "         | "            |                                         | 12                    | 240    | "         | "                   | 111                | "                | "              | "                 | "               | "             | 0.5°                  |
| 217      | "          | "         | "            |                                         | 12                    | 240    | "         | "                   | 333                | "                | "              | "                 | "               | "             | 0.5°                  |
| 217A     | "          | "         | "            |                                         | 2                     | 24     | "         | "                   | 333                | "                | 0.75           | "                 | 6K              | "             | 1°                    |
| 218      | "          | "         | "            |                                         | 12                    | 240    | "         | "                   | 444                | "                | 0.5            | "                 | 36K             | "             | 0.5°                  |
| 218A     | "          | "         | "            |                                         | 2                     | 24     | "         | "                   | 444                | "                | 1.0            | "                 | 6K              | "             | 1°                    |

| CASE NO. | STUDY      | PLOT           | B.L.H. NO. S | RESOLUTION $\Delta\theta, \Delta\sigma$ | BLADE NO. $\Delta mB$ | mB MAX | CHORD INS. | FORCE ANGLE $\beta$ | ROTOR SPEED R.P.M. | ROTOR RADIUS FT. | $M_e$ | SPAN DISTRIBUTION | L <sub>ST</sub> | OBS DIST. FT. | $\int \Delta\psi$ |
|----------|------------|----------------|--------------|-----------------------------------------|-----------------------|--------|------------|---------------------|--------------------|------------------|-------|-------------------|-----------------|---------------|-------------------|
| 219      | FLAT SPEC. | mB F/O         | 1-200        |                                         | 12                    | 240    | 16         | 6°                  | 555                | 30               | 0.5   | RECT 10%          | 36K             | 300           | 0.5°              |
| 219A     | "          | "              | "            |                                         | 2                     | 24     | "          | 6°                  | 555                | "                | 1.25  | "                 | 6K              | "             | 1°                |
| 220      | "          | "              | "            |                                         | 12                    | 240    | "          | 0°                  | 222                | "                | 0.5   | "                 | 36K             | "             | 0.5°              |
| 220A     | "          | "              | "            |                                         | 2                     | 24     | "          | 0°                  | "                  | "                | "     | "                 | 6K              | "             | 1°                |
| 221      | "          | "              | "            |                                         | 12                    | 240    | "          | 24°                 | "                  | "                | "     | "                 | 36K             | "             | 0.5°              |
| 221A     | "          | "              | "            |                                         | 2                     | 24     | "          | 24°                 | "                  | "                | "     | "                 | 6K              | "             | 1°                |
| 222      | "          | "              | "            |                                         | 12                    | 240    | 1          | 6°                  | "                  | "                | "     | "                 | 36K             | "             | 0.5°              |
| 222A     | "          | "              | "            |                                         | 2                     | 24     | 1          | "                   | "                  | "                | "     | "                 | 6K              | "             | 1°                |
| 223      | "          | "              | "            |                                         | 12                    | 240    | 64         | "                   | "                  | "                | "     | "                 | 36K             | "             | 0.5°              |
| 223A     | "          | "              | "            |                                         | 2                     | 24     | 64         | "                   | "                  | "                | "     | "                 | 6K              | "             | 1°                |
| 224      | "          | "              | "            | 20°                                     | 12                    | 48     | 16         | "                   | "                  | "                | "     | "                 | 36K             | "             | 0.5°              |
| 224A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | "                  | "                | "     | "                 | "               | "             | 1°                |
| 225      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 111                | "                | 0.25  | "                 | "               | "             | "                 |
| 225A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 111                | "                | "     | "                 | "               | "             | "                 |
| 226      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 333                | "                | 0.75  | "                 | "               | "             | "                 |
| 226A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 333                | "                | "     | "                 | "               | "             | "                 |
| 227      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 444                | "                | 1.0   | "                 | "               | "             | "                 |
| 227A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 444                | "                | 1.0   | "                 | "               | "             | "                 |
| 228      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 555                | "                | 1.25  | "                 | "               | "             | "                 |
| 228A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | "                   | 555                | "                | 1.25  | "                 | "               | "             | "                 |
| 229      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | 0°                  | 222                | "                | 0.5   | "                 | "               | "             | "                 |
| 229A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | 0°                  | "                  | "                | "     | "                 | "               | "             | "                 |
| 230      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | 24°                 | "                  | "                | "     | "                 | "               | "             | "                 |
| 230A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | "          | 24°                 | "                  | "                | "     | "                 | "               | "             | "                 |
| 231      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | 1          | 6°                  | "                  | "                | "     | "                 | "               | "             | "                 |
| 231A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | 1          | "                   | "                  | "                | "     | "                 | "               | "             | "                 |
| 232      | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | 64         | "                   | "                  | "                | "     | "                 | "               | "             | "                 |
| 232A     | "          | ELEVATION PLAN | "            | "                                       | "                     | "      | 64         | "                   | "                  | "                | "     | "                 | "               | "             | "                 |
| 233      | "          | mB F/O         | "            | "                                       | "                     | 240    | 16         | "                   | "                  | "                | "     | CONST             | "               | "             | 0.5°              |
| 233A     | "          | "              | "            | "                                       | 2                     | 24     | "          | "                   | "                  | "                | "     | "                 | 6K              | "             | 1°                |
| 234      | "          | "              | "            | "                                       | 12                    | 240    | "          | "                   | "                  | "                | "     | RECT 0.3%         | 36K             | "             | 0.5°              |
| 234A     | "          | "              | "            | "                                       | 2                     | 24     | "          | "                   | "                  | "                | "     | "                 | 6K              | "             | 1°                |

| CASE NO. | STUDY     | PLOT      | B.L.H. NO. S | RESOLUTION $\Delta\theta, \Delta\sigma$ | BLADE NO. $\Delta mB$ | mB MAX | CHORD INS | FORCE ANGLE $\beta$ | ROTOR SPEED R.P.M. | ROTOR RADIUS FT. | $M_e$ | SPAN DISTRI-BUTION | $L_{ST}$         | OBS DIST. FT. | $\int INT \Delta\psi$ |
|----------|-----------|-----------|--------------|-----------------------------------------|-----------------------|--------|-----------|---------------------|--------------------|------------------|-------|--------------------|------------------|---------------|-----------------------|
| 235      | FLAT SPEC | mB F/O    | 1-200        |                                         | 12                    | 240    | 16        | 6°                  | 222                | 30               | 0.5   | ZERO LIFT          | 36K              | 300           | 0.5°                  |
| 235A     | "         | "         | "            |                                         | 2                     | 24     | "         | "                   | "                  | "                | "     | "                  | 6K               | "             | 1°                    |
| 236      | "         | ELEVATION | "            | 20°                                     | 12                    | 48     | "         | "                   | "                  | "                | "     | CONST              | 36K              | "             | 0.5°                  |
| 236A     | "         | PLAN      | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | "                | "             | 1°                    |
| 237      | "         | ELEVATION | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | RECT 0.3%          | "                | "             | 0.5°                  |
| 237A     | "         | PLAN      | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | "                | "             | 1°                    |
| 238      | "         | ELEVATION | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | ZERO LIFT          | "                | "             | "                     |
| 238A     | "         | PLAN      | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | "                | "             | "                     |
| 239      | AZM.FN.   | mB F/O    | 1-300        |                                         | "                     | 348    | "         | "                   | "                  | "                | "     | RECT 10%           | RECT-ANGU-LAR    | "             | 0.5°                  |
| 240      | "         | "         | "            |                                         | "                     | "      | "         | "                   | "                  | "                | "     | "                  | LAR HALF CO-SINE | "             | 0.5°                  |
| 240A     | "         | "         | "            |                                         | 2                     | 24     | "         | "                   | "                  | "                | "     | "                  | "                | "             | 1°                    |
| 241      | "         | "         | "            |                                         | 12                    | 348    | "         | "                   | "                  | "                | "     | "                  | FULL SINE        | "             | 0.5°                  |
| 241A     | "         | "         | "            |                                         | 2                     | 24     | "         | "                   | "                  | "                | "     | "                  | "                | "             | 1°                    |
| 242      | "         | ELEVATION | "            | 10°                                     | 48                    | 192    | "         | "                   | "                  | "                | "     | "                  | RECT-ANGU-LAR    | "             | 0.5°                  |
| 243      | "         | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | HALF CO-SINE     | "             | "                     |
| 244      | "         | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | FULL SINE        | "             | "                     |
| 245      | "         | PLAN      | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | RECT-ANGU-LAR    | "             | "                     |
| 246      | "         | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | HALF CO-SINE     | "             | "                     |
| 247      | "         | "         | "            | "                                       | "                     | "      | "         | "                   | "                  | "                | "     | "                  | FULL SINE        | "             | "                     |
| 248      | FLAT SPEC | ELEV PLAN | 1-200        | 20°, 20°                                | 12                    | 48     | "         | "                   | "                  | "                | "     | "                  | 36K              | 26-120        | "                     |

#### 4. List of figures

##### 1 Properties of blade loading harmonics

(figure numbers are shown in the columns)

##### 1.1 Far field

|                             |                             | s=0 | s=12 | s=48 |
|-----------------------------|-----------------------------|-----|------|------|
| Effect of span distribution | mB falloff                  | 1   | 15   | 29   |
|                             | polar elevation-0.3%        | 2   | 16   | 30   |
|                             | -10%                        | 3*  | 17*  | 31*  |
|                             | -constant                   | 4   | 18   | 32   |
|                             | -triangular                 | 5   | 19   | 33   |
|                             | -zero lift                  | 6   | 20   | 34   |
| Effect of chord width       | mB falloff                  | 7   | 21   | 35   |
| Effect of force angle       | mB falloff                  | 8   | 22   | 36   |
|                             | polar elevation - $0^\circ$ | 9   | 23   | 37   |
|                             | - $6^\circ$                 | 3*  | 17*  | 31*  |
|                             | - $24^\circ$                | 10  | 24   | 38   |
| Effect of Mach number       | mB falloff                  | 11  | 25   | 39   |
|                             | polar elevation - 0.25      | 12  | 26   | 40   |
|                             | - 0.5                       | 3*  | 17*  | 31*  |
|                             | - 0.75                      | 13  | 27   | 41   |
|                             | - 1.25                      | 14  | 28   | 42   |

\* STD CASE.

##### 1.2 Near field

|                                                       |                            |   |    |    |
|-------------------------------------------------------|----------------------------|---|----|----|
| Effect of span distribution, observer distance mB = 4 |                            | 1 |    |    |
| Effect of mB number                                   | observer distance          | 2 | 6  | 16 |
|                                                       | polar elevation - mB = 4   | 3 |    |    |
|                                                       | - mB = 6                   |   | 7  |    |
|                                                       | - mB = 12                  |   | 8  |    |
|                                                       | - mB = 18                  |   | 9  |    |
| Effect of rotor speed                                 | observer distance - mB = 4 | 4 |    |    |
|                                                       | - mB = 6                   |   | 10 |    |
|                                                       | - mB = 12                  |   | 11 |    |
|                                                       | - mB = 18                  |   | 12 |    |

|                        |                            |     |      |      |
|------------------------|----------------------------|-----|------|------|
|                        |                            | s=0 | s=12 | s=48 |
| Effect of rotor radius | observer distance - mB = 4 | 5   |      |      |
|                        | - mB = 6                   |     | 13   |      |
|                        | - mB = 12                  |     | 14   |      |
|                        | - mB = 18                  |     | 15   |      |

## 2 Composite blade loading spectra

|     |                                                            | <u>mB FALLOFF</u> |              | <u>POLAR</u> |      |
|-----|------------------------------------------------------------|-------------------|--------------|--------------|------|
|     |                                                            | LOW<br>RES.       | HIGH<br>RES. | ELEVA        | PLAN |
| 2.1 | <u>Simple B.L.H. addition <math>s_{12} + s_{24}</math></u> | 1                 |              | 2            | 3    |
| 2.2 | <u>Continuous B.L. spectrum</u>                            |                   |              |              |      |
|     | Effect of B.L.H. falloff                                   | 1*                | 2*           | 3*           | 5*   |
|     | (inphase B.L.H.)                                           | 1                 | 2            | 4            | 6    |
|     | Effect of B.L.H. phase                                     | 7                 |              | 8            | 10   |
|     | (flat B.L. spectrum)                                       | 7                 |              | 9            | 11   |
|     | uncorrelated                                               | 7                 |              |              |      |
|     | phase                                                      |                   |              |              |      |
|     | inphase                                                    | 7*                |              | 3*           | 5*   |
| 2.3 | <u>Flat B.L. spectrum</u>                                  |                   |              |              |      |
|     | Effect of span distribution                                |                   |              |              |      |
|     | 0.3%                                                       | 1                 | 2            | 3            | 7    |
|     | 10%                                                        | 1*                | 2*           | 4*           | 8*   |
|     | constant                                                   | 1                 | 2            | 5            | 9    |
|     | zero lift                                                  | 1                 | 2            | 6            | 10   |
|     | Effect of chord width                                      |                   |              |              |      |
|     | 1"                                                         | 11                | 12           | 13           | 15   |
|     | 16"                                                        | 11*               | 12*          | 4*           | 8*   |
|     | 64"                                                        | 11                | 12           | 14           | 16   |
|     | Effect of force angle                                      |                   |              |              |      |
|     | 0°                                                         | 17                | 18           | 19           | 21   |
|     | 6°                                                         | 17*               | 18*          | 4*           | 8*   |
|     | 24°                                                        | 17                | 18           | 20           | 22   |
|     | Effect of Mach number                                      |                   |              |              |      |
|     | 0.25                                                       | 23                | 24           | 25           | 29   |
|     | 0.5                                                        | 23*               | 24*          | 4*           | 8*   |
|     | 0.75                                                       | 23                | 24           | 26           | 30   |
|     | 1.0                                                        | 23                | 24           | 27           | 31   |
|     | 1.25                                                       | 23                | 24           | 28           | 32   |
|     | Effect of observer distance                                |                   |              |              |      |
|     | 300'                                                       | 33*               |              | 4*           | 8*   |
|     | 120'                                                       | 33                |              | 34           | 38   |
|     | 60'                                                        | 33                |              | 35           | 39   |
|     | 30'                                                        | 33                |              | 36           | 40   |
|     | 26'                                                        |                   |              | 37           | 41   |
|     | Effect of number of B.L.H.                                 |                   |              |              |      |
|     | 1 → 100                                                    | 42                |              |              |      |
|     | 1 → 200                                                    | 42                |              |              |      |

|     |                                |             | <u>mB FALLOFF</u> |              | <u>POLAR</u> |      |
|-----|--------------------------------|-------------|-------------------|--------------|--------------|------|
|     |                                |             | LOW<br>RES.       | HIGH<br>RES. | ELEVA        | PLAN |
| 2.4 | <u>B.L. azimuth functions</u>  |             |                   |              |              |      |
|     | Effect of load solidity        | 1%          | 1*                | 2*           | 3*           | 6*   |
|     |                                | 10%         | 1                 | 2            | 4            | 7    |
|     |                                | 50%         | 1                 | 2            | 5            | 8    |
|     | Effect of number of excursions | 1           | 9*                | 10*          | 3*           | 6*   |
|     |                                | 4           | 9                 | 10           | 11           | 13   |
|     |                                | 16          | 9                 | 10           | 12           | 14   |
|     | Effect of type of function     | rectangular | 15*               |              | 17*          | 20*  |
|     |                                | half cosine | 15                | 16           | 18           | 21   |
|     |                                | full sine   | 15                | 16           | 19           | 22   |

### 3 Illustrations

|                                  |     |
|----------------------------------|-----|
| The standard case                | 3.1 |
| Observer definition around rotor | 3.2 |
| Span distribution definitions    | 3.3 |
| B.L. azimuth functions           | 3.4 |

# LIST OF SYMBOLS AND ABBREVIATIONS

|            |                                                                       |
|------------|-----------------------------------------------------------------------|
| a          | blade chord width                                                     |
| B          | blade number                                                          |
| B.L.       | blade loading                                                         |
| B.L.H.     | blade loading harmonic                                                |
| E          | number of blade loading function excursions                           |
| F/F        | far field                                                             |
| $L_o$      | steady lift per blade                                                 |
| $L_{OT}$   | total steady lift $L_{OT} = L_o B$                                    |
| $L_S$      | S harmonic blade loading smplitude                                    |
| $L_{ST}$   | total arithmetic blade loading amplitude of order S, $L_{ST} = L_S B$ |
| m          | sound pressure harmonic number                                        |
| $M_e$      | effective Mach number                                                 |
| N          | rotor frequency Hz                                                    |
| N/F        | near field                                                            |
| $r_e$      | effective rotor radius                                                |
| $r_T$      | rotor tip radius                                                      |
| R          | observer distance from rotor centre                                   |
| S          | blade loading harmonic number                                         |
| S.P.L.     | sound pressure level dB ref. 0.0002 dynes/cm <sup>2</sup>             |
| W          | blade loading function width                                          |
| $\alpha_S$ | blade loading coefficient $\alpha_S = \frac{L_S}{L_o}$                |
| $\beta$    | force (or effective blade lift) angle                                 |
| $\Delta L$ | load change                                                           |
| $\theta$   | observer azimuth angle (tail $\theta = 0^\circ$ )                     |
| $\rho$     | load solidity $\rho = W/2\pi r_e$                                     |
| $\sigma$   | observer elevation angle (rotor plane $\sigma = 0^\circ$ )            |
| $\phi_S$   | blade loading harmonic phase, order S.                                |

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J. Sound Vib. (1969) 9 (2).  
Sound radiation from a lifting rotor generated  
by asymmetric disc loading.
2. WRIGHT, S.E. 1969. I.S.V.R. Technical Report No. 14.  
Theoretical study of rotational noise.
3. TANNA, H.K. 1968. I.S.V.R. Technical Report No. 13.  
Computer programme for the prediction of rotational  
noise, due to fluctuating loading on rotor blades.

## B.L.H. PROPERTIES

total lift  $L_{OT} = 12\,000 \text{ lbs} = B L_0$   
B.L.H. coefficient  $\alpha_S = 1 = \frac{L_S}{L_0}$   
 $S^{\text{th}}$  B.L.H. amplitude  $L_S = \text{Variable (fn of B)}$   
total arithmetic B.L.H. amplitude  $L_{ST} = 12\,000 \text{ lbs}$   
blade force angle  $\beta = 6^\circ$   
effective tip Mach No  $M_e = 0.5$   
effective tip radius  $r_e = 24 \text{ ft}$   
tip radius  $r_T = 30 \text{ ft}$   
rotational frequency  $N = 3.7 \text{ Hz}$   
span distribution Dist = Rectangular 10 %  
chord width  $a = 16 \text{ in}$

## FLAT BLADE LOADING SPECTRUM

as B.L.H. properties

B.L.H. spectrum range  $S = 1-200$   
B.L.H. coefficient  $\alpha_S = 1$   
B.L.H. phase  $\phi_S = 0^\circ$   
 $S^{\text{th}}$  B.L.H. amplitude  $L_S = 3000 \text{ lbs/blade}$   
or  $83.3 \text{ lbs/in}$   
 $L_{ST} = \text{Variable (fn of B)}$

## B.L. AZIMUTH FUNCTIONS

as B.L.H. properties

Type of function  $fn = \text{Rectangular}$   
load solidity  $P = 1\%$   
Number of excursions  $E = 1$   
 $L_S \text{ Max} = 1 \text{ lb/in or } 36 \text{ lbs/blade}$   
load change  $\frac{\Delta L}{L_0} = 60\% \text{ or } \Delta L = 50 \text{ lbs/in}$

Fig 3.1. The standard cases

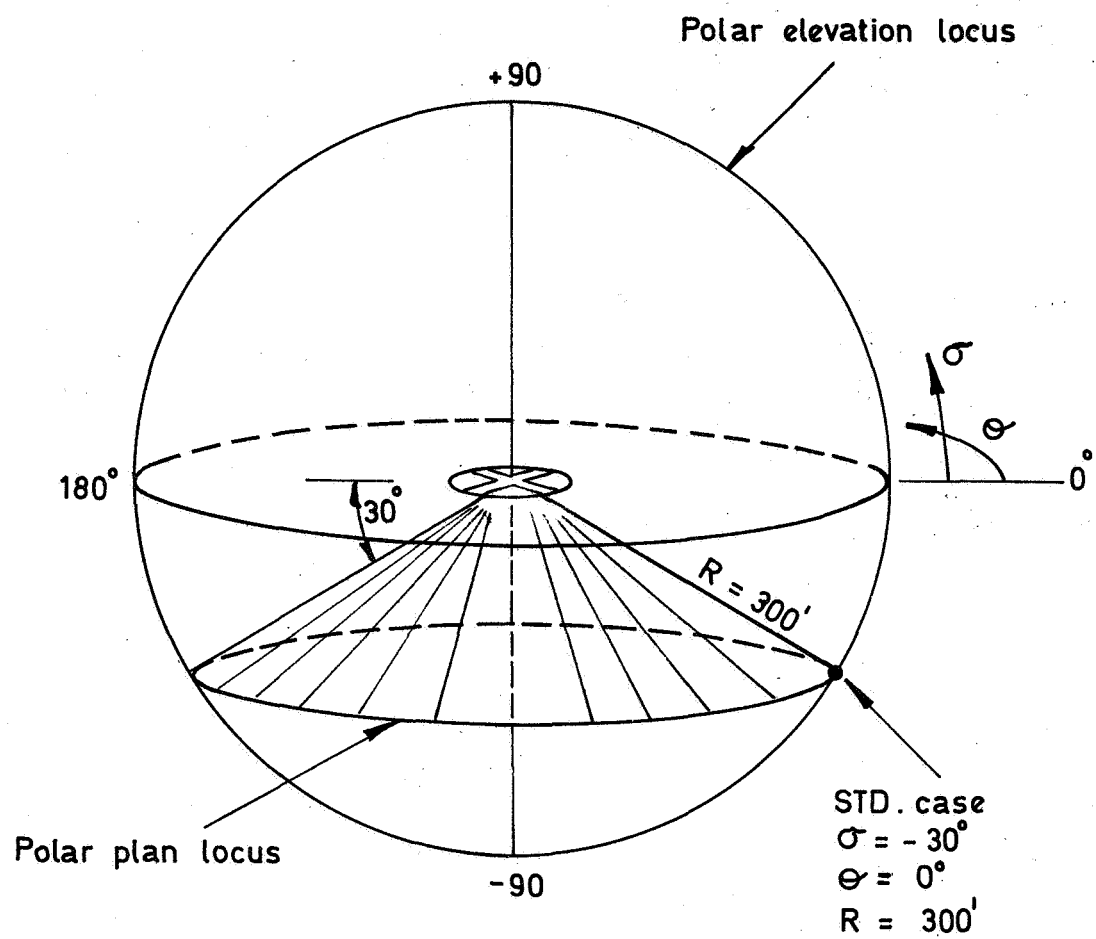


Fig. 3.2 Observer definition around rotor .

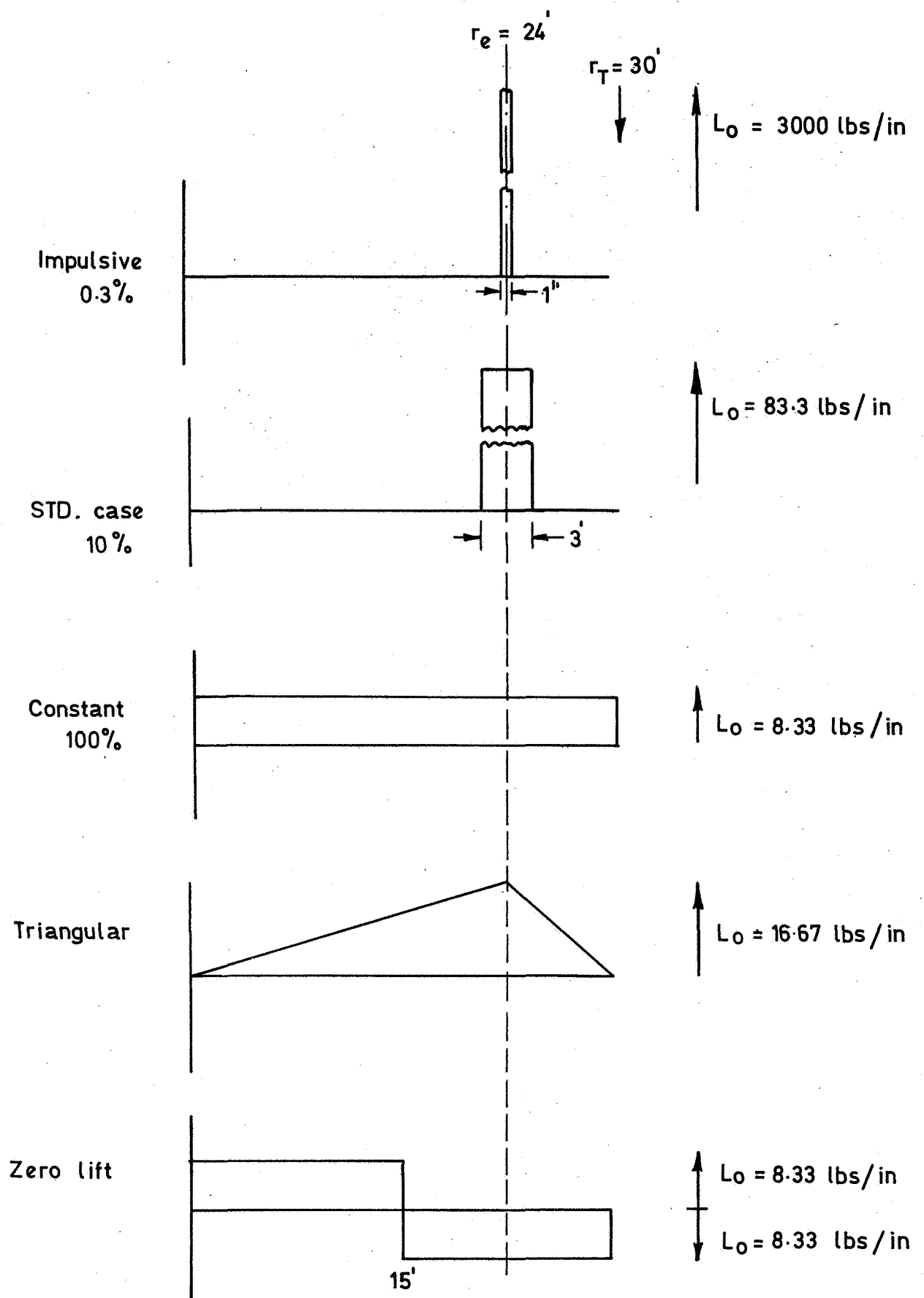


Fig. 3.3 Span distribution definitions .

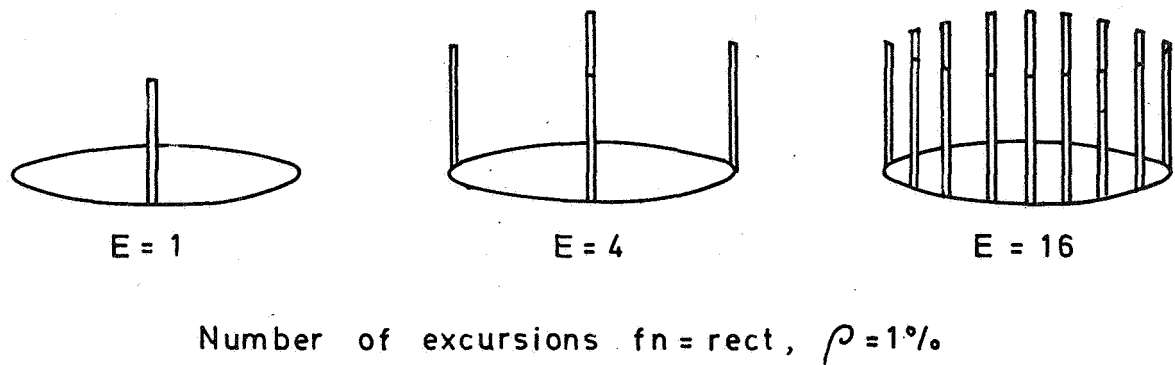
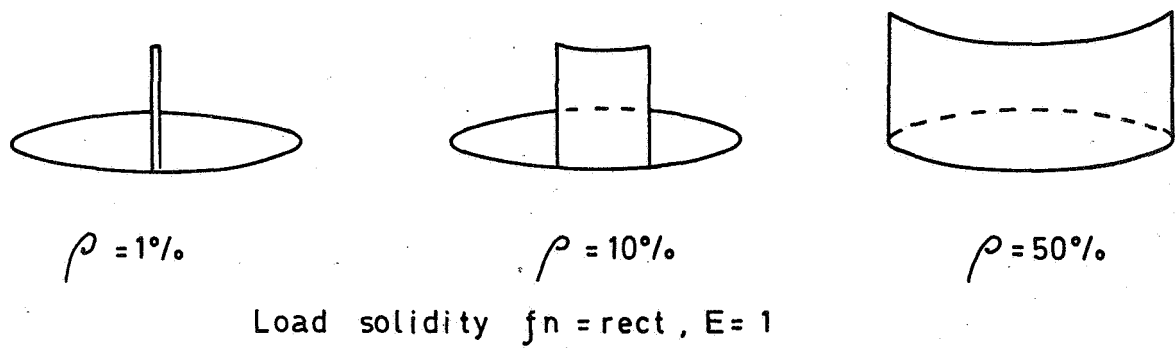
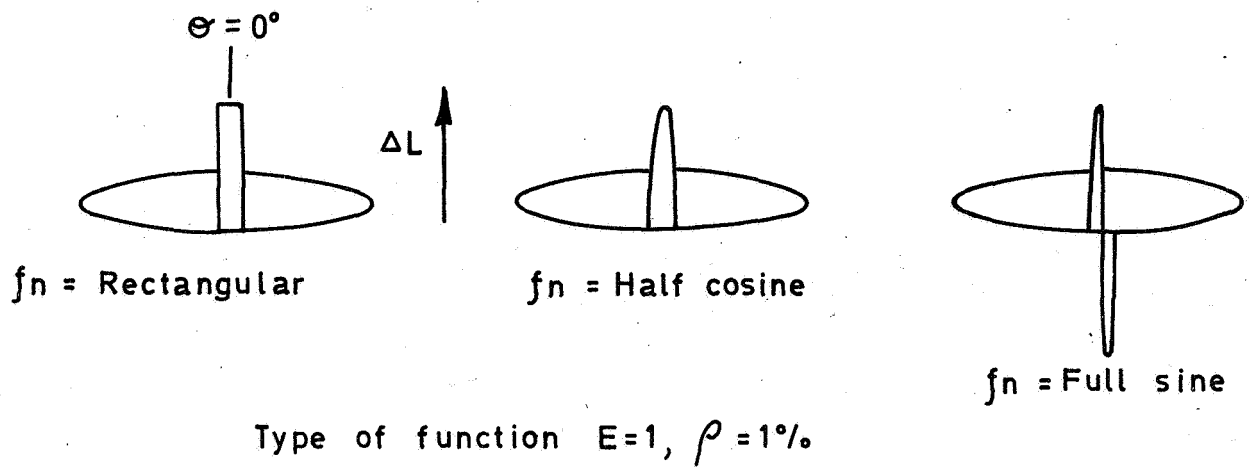


Fig. 3.4 B.L. Azimuth functions

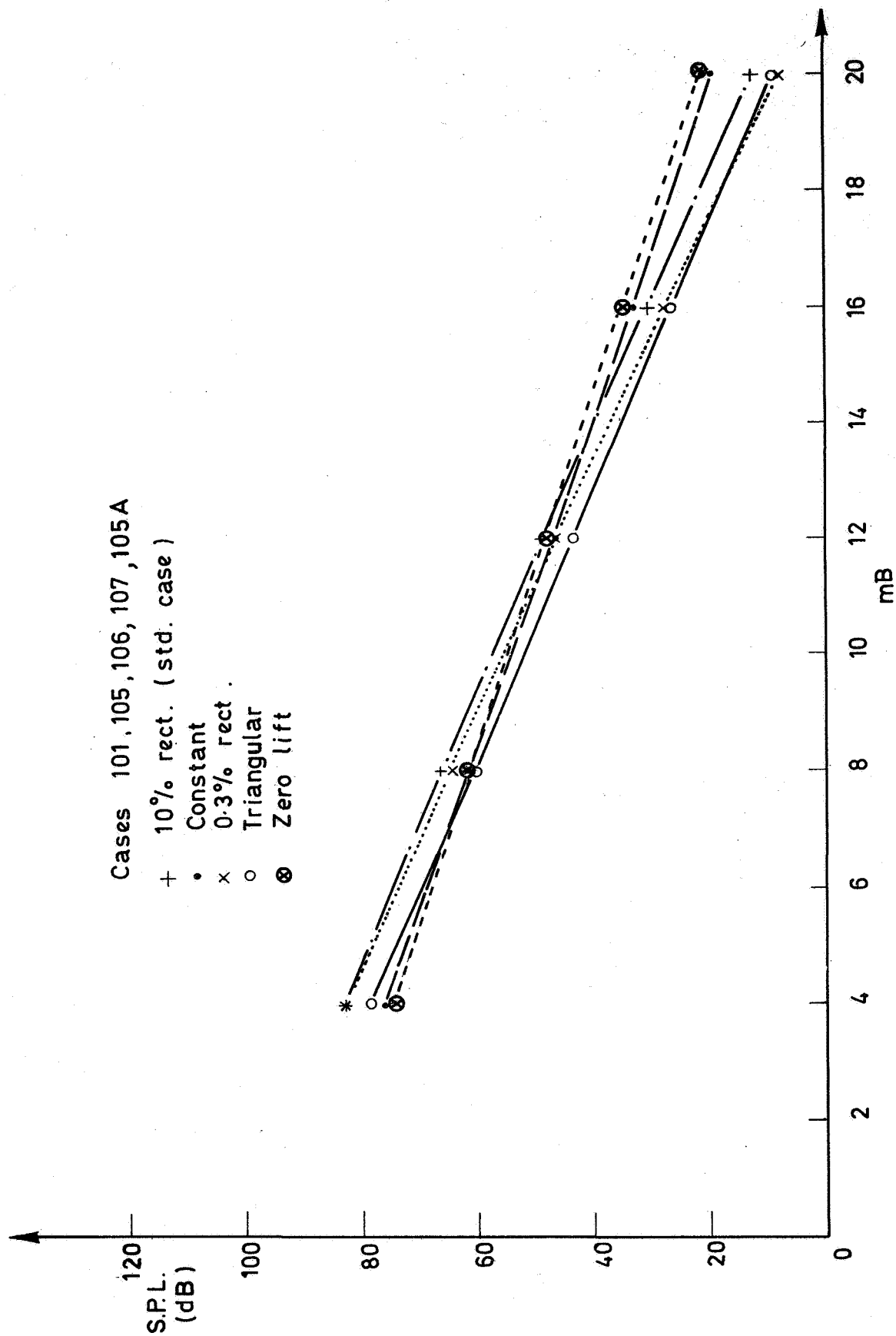


Fig.11.1 Effect of span distribution.  $S = 0$   $\sigma = -30^\circ$

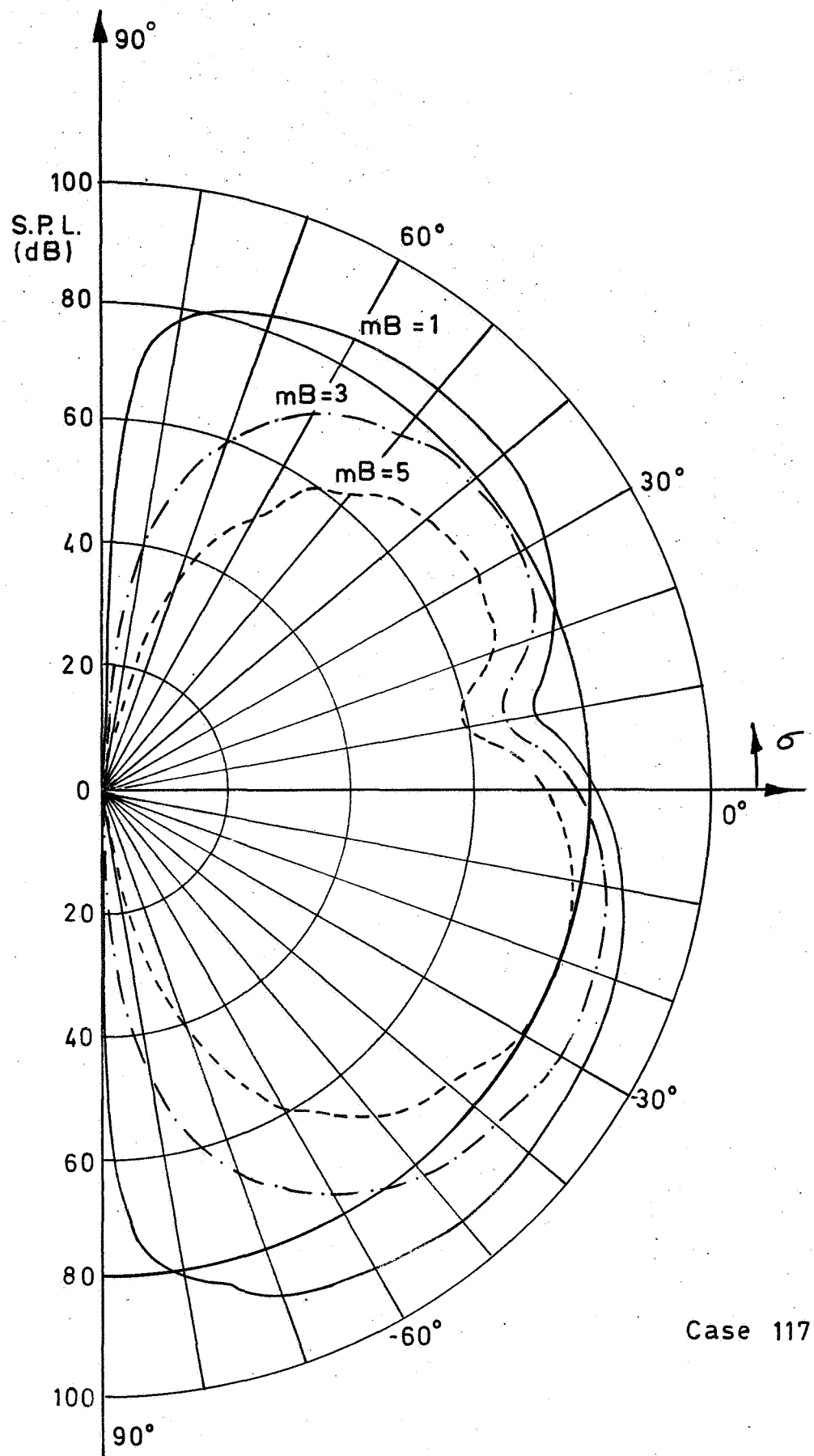


Fig.1-1-2 Effect of distribution  
Rect. 0.3%  $S=0$

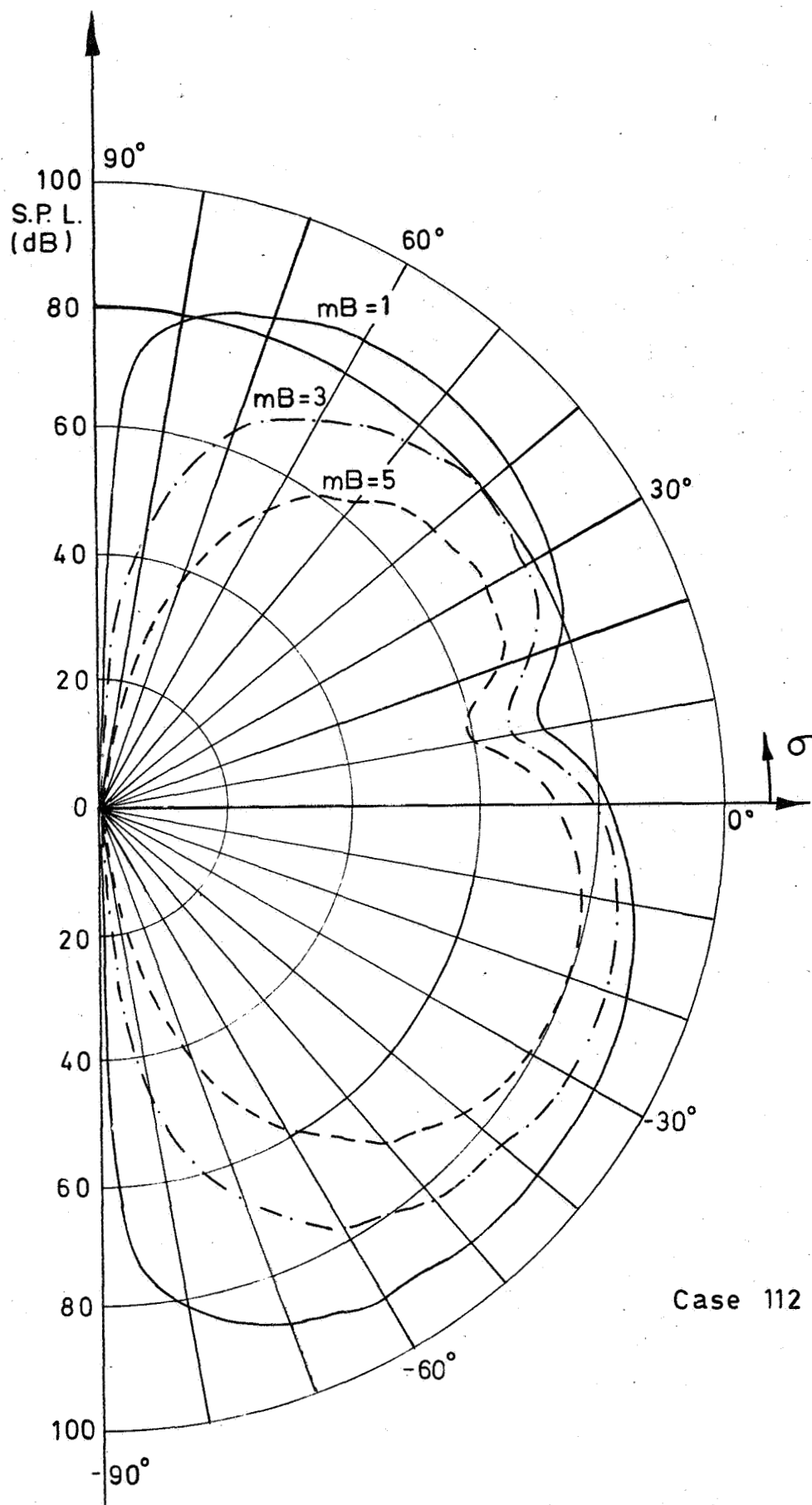
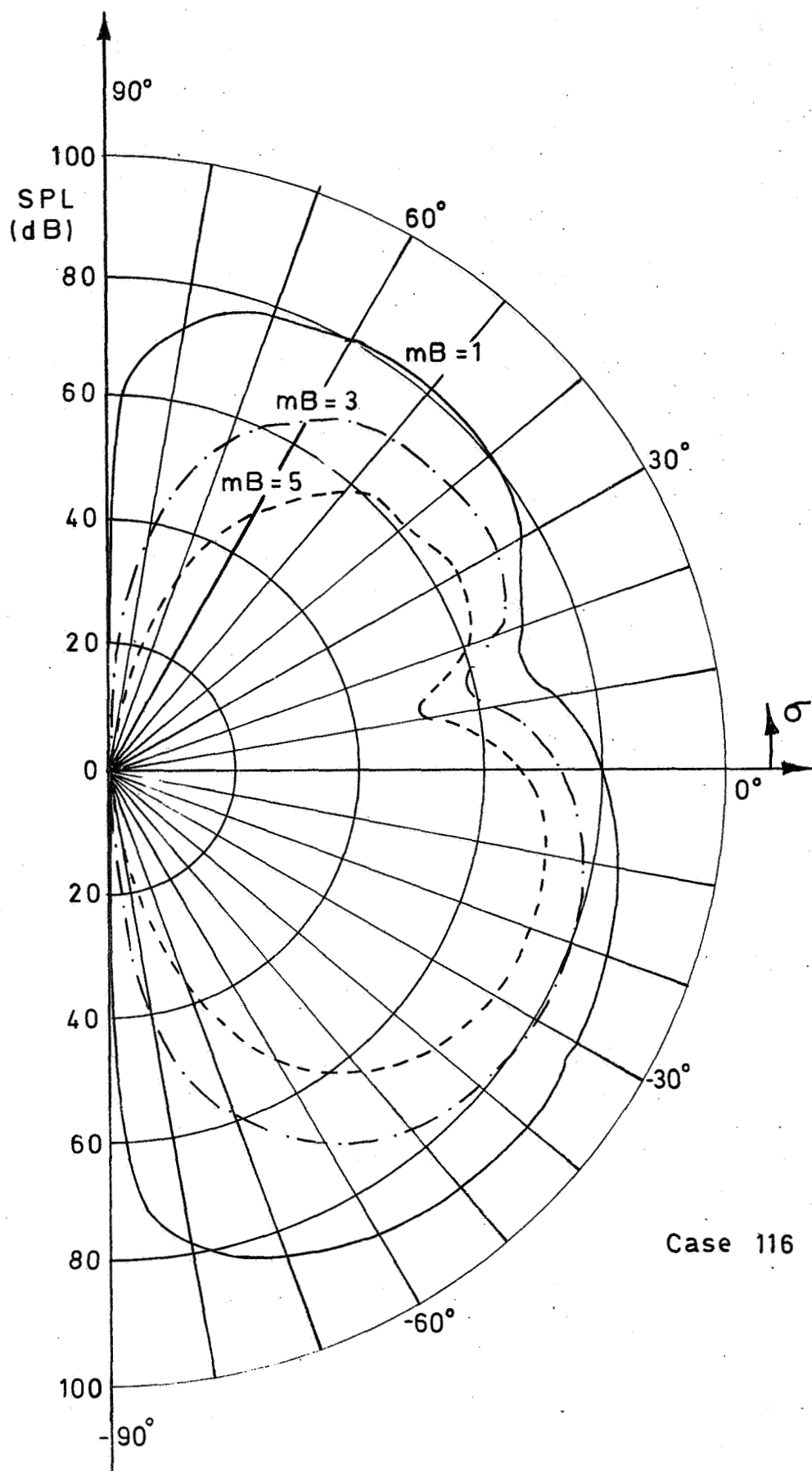
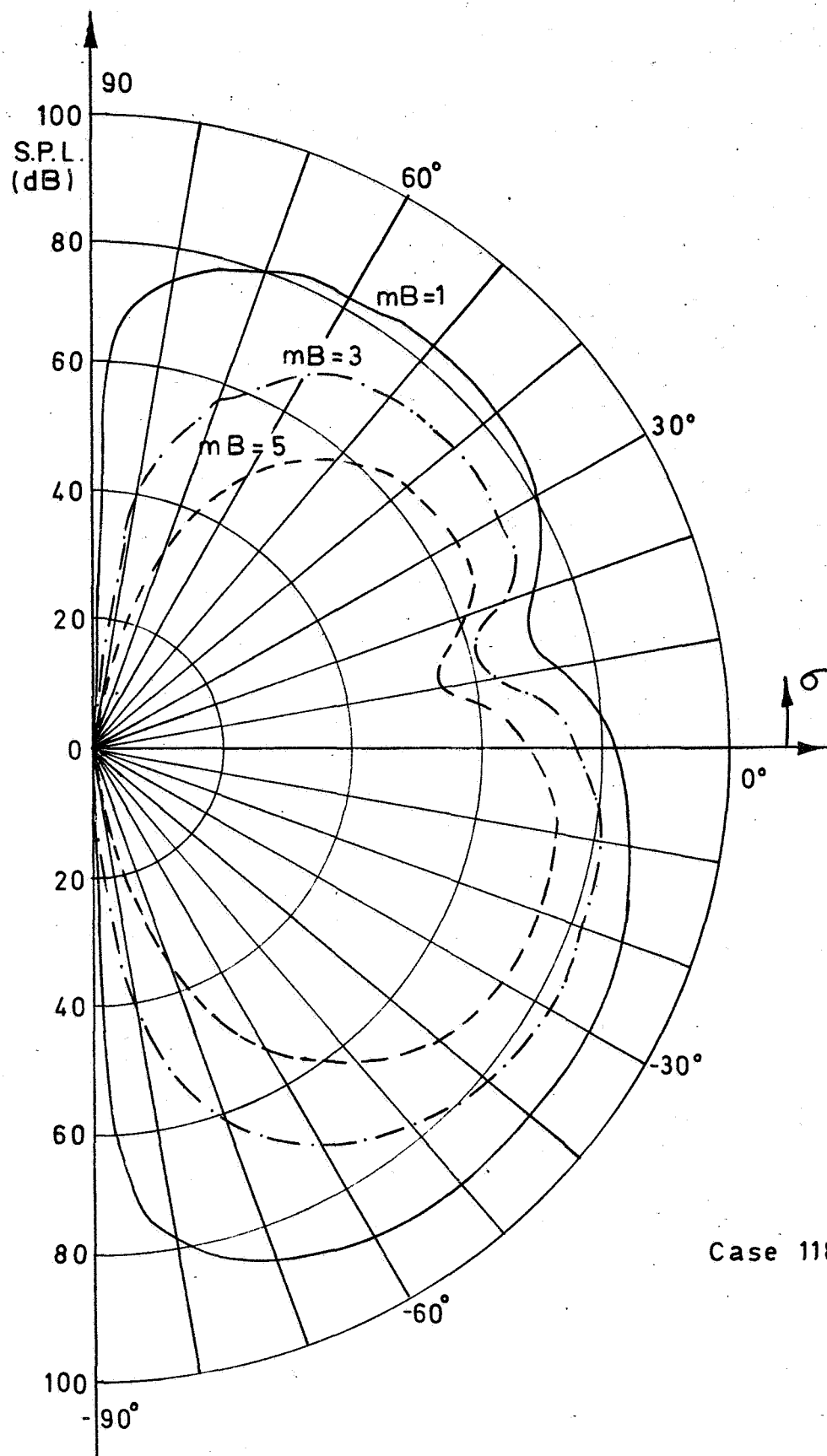


Fig 1-13 Effect of span distribution,  
Rect. 10% (Std. case)  $S=0$



Case 116

Fig. 1.1.4 Effect of span distribution  
Distribution = const.  $S=0$



Case 118

Fig. 1.1.5 Effect of distribution  
Triangular  $S=0$

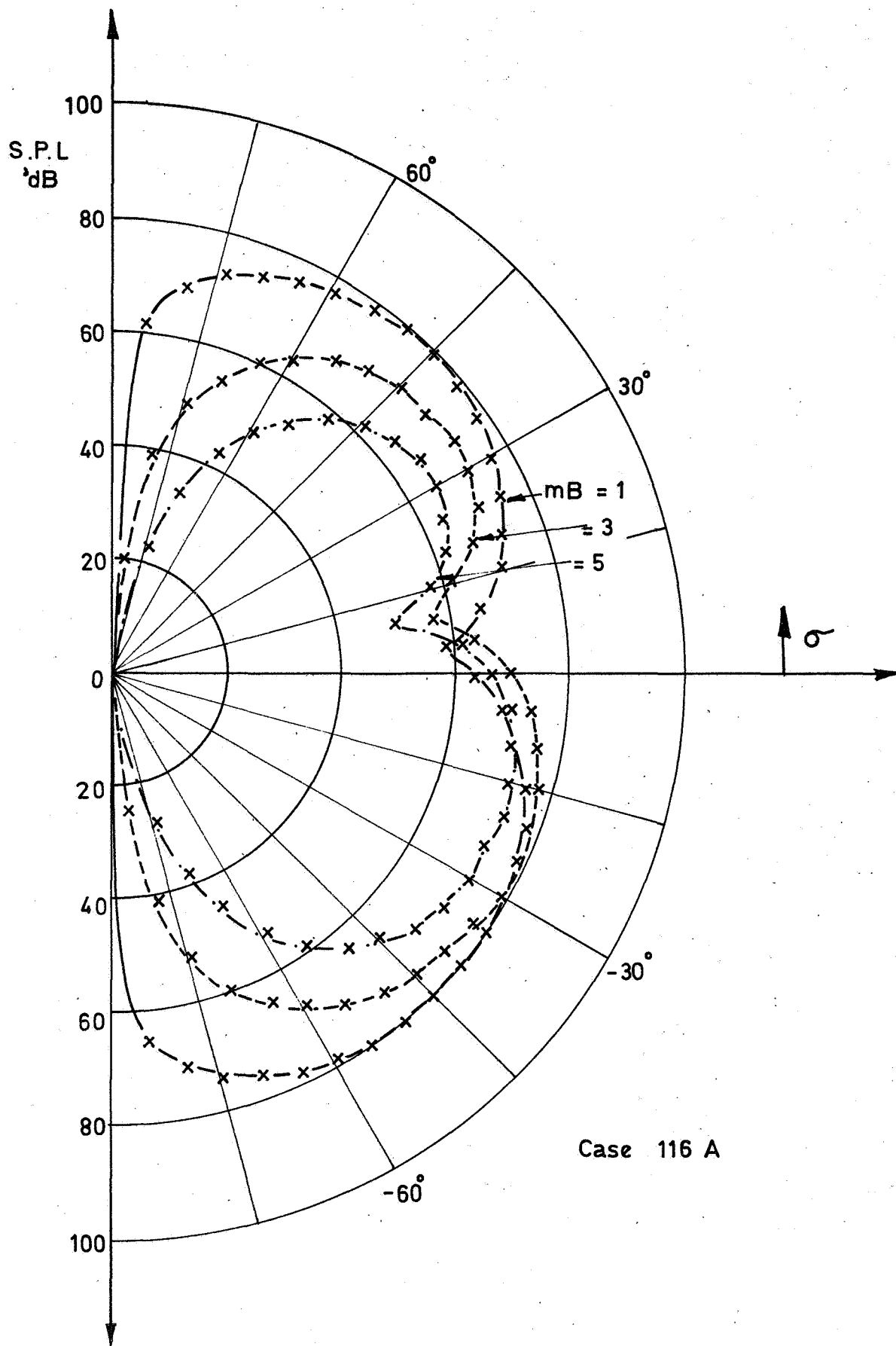


Fig.11.6 Effect of distribution , zero lift  $S = 0$  .

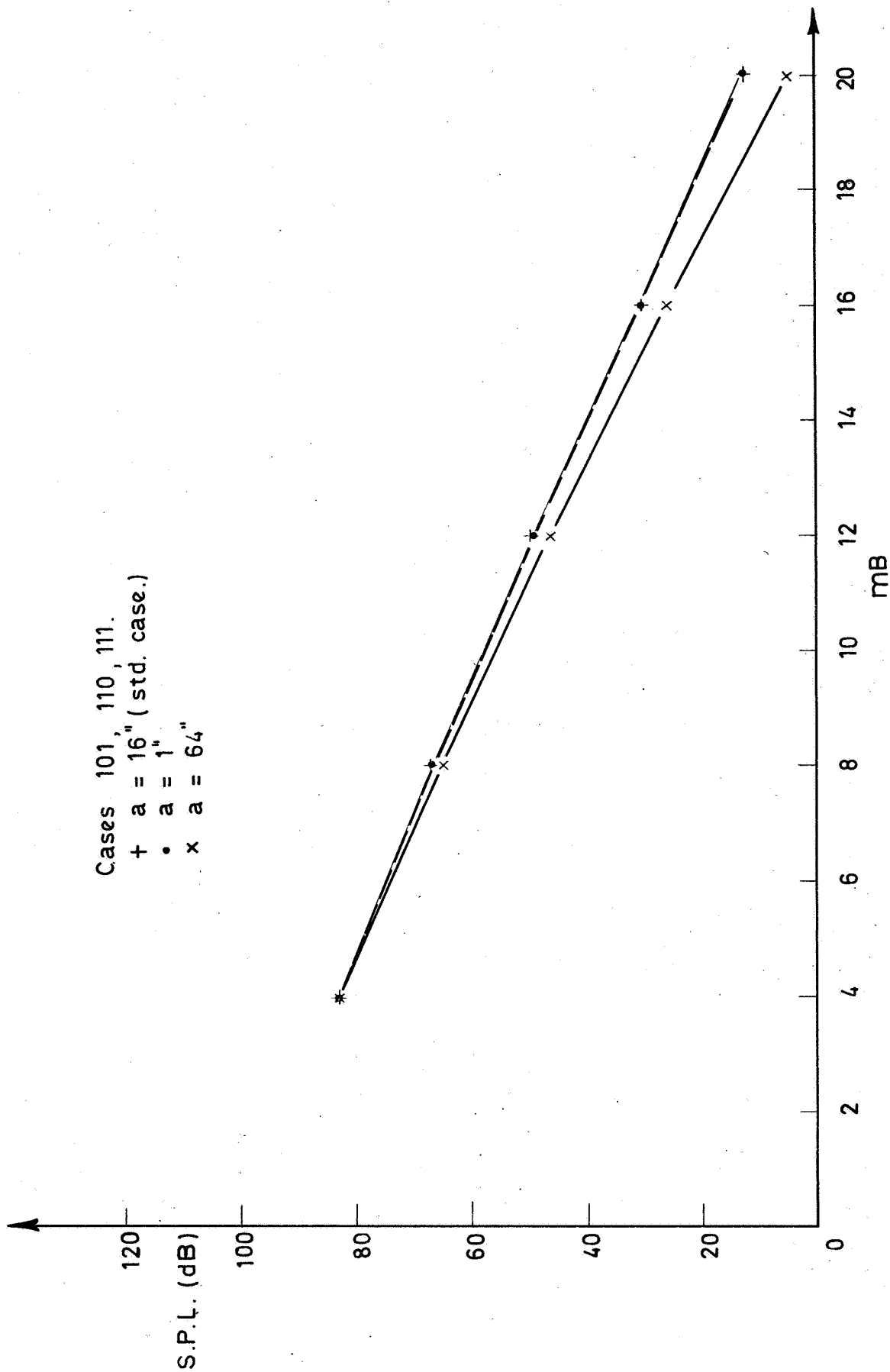


Fig.1.1.7 Effect of chord width .  $S = 0$  .  $\sigma = -30^\circ$

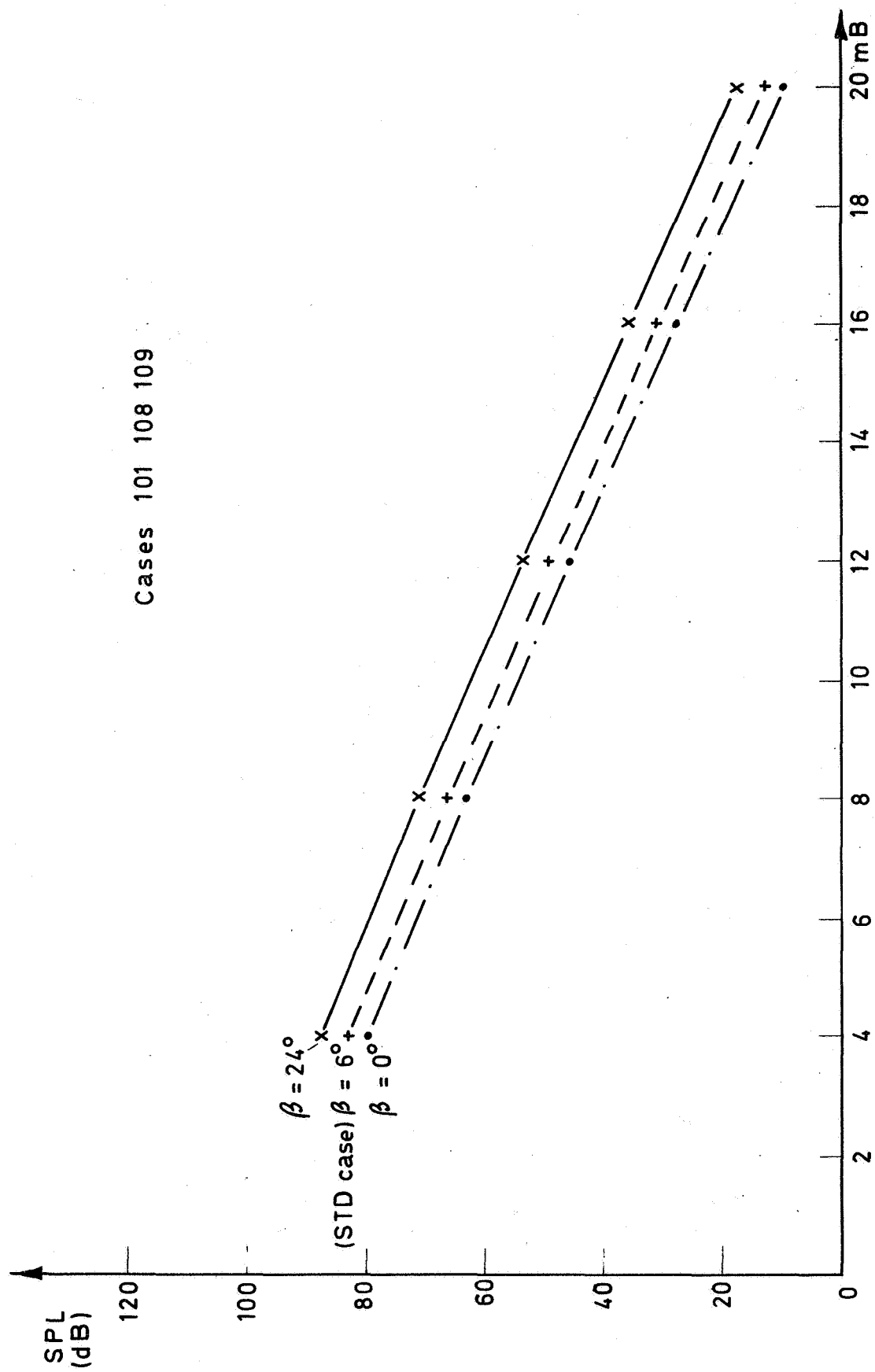


Fig.11.8 Effect of force angle  $s=0$ ,  $\sigma = -30^\circ$

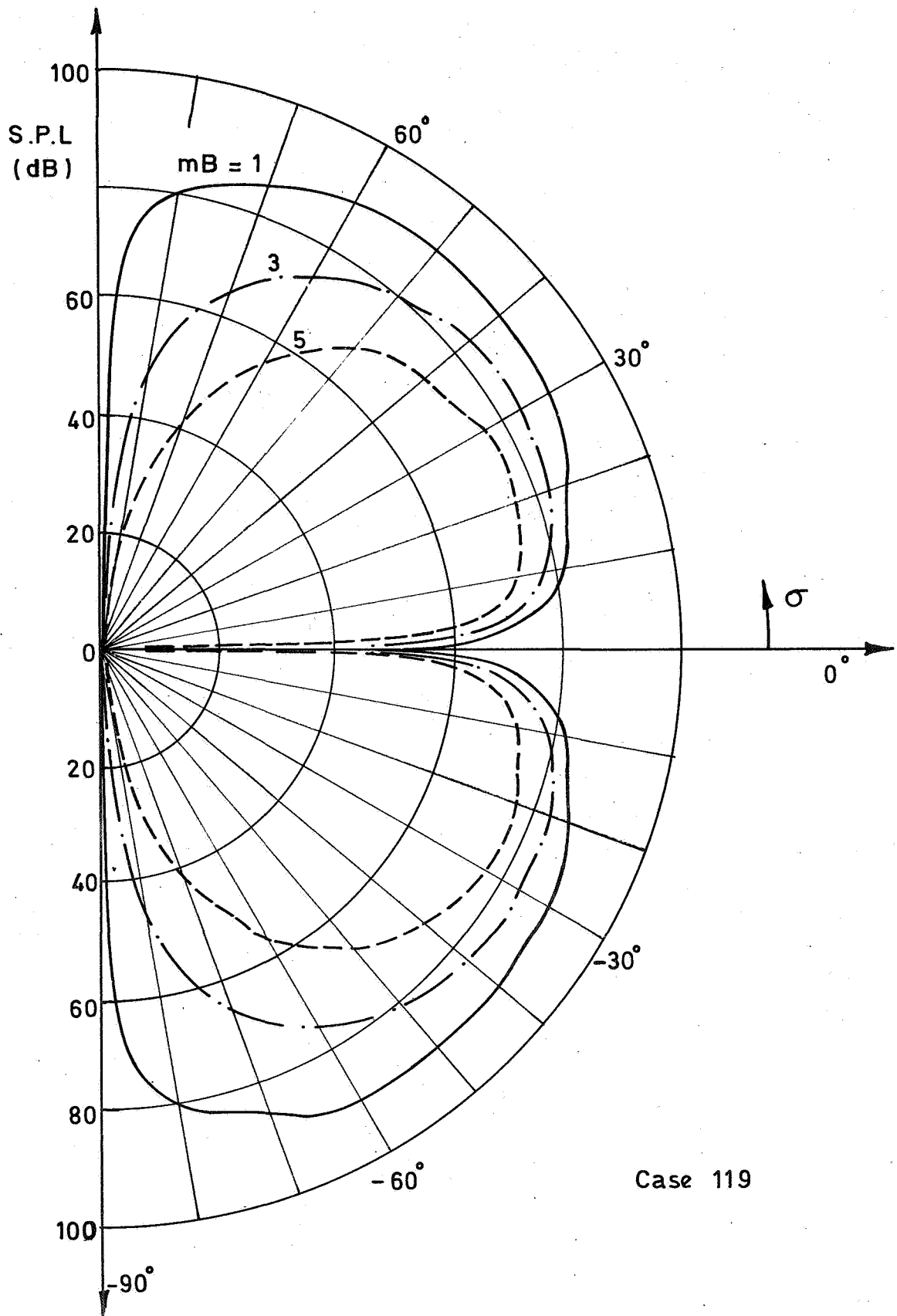


Fig.1.1-9. Effect of force angle  $\beta = 0^\circ$   $s = 0$

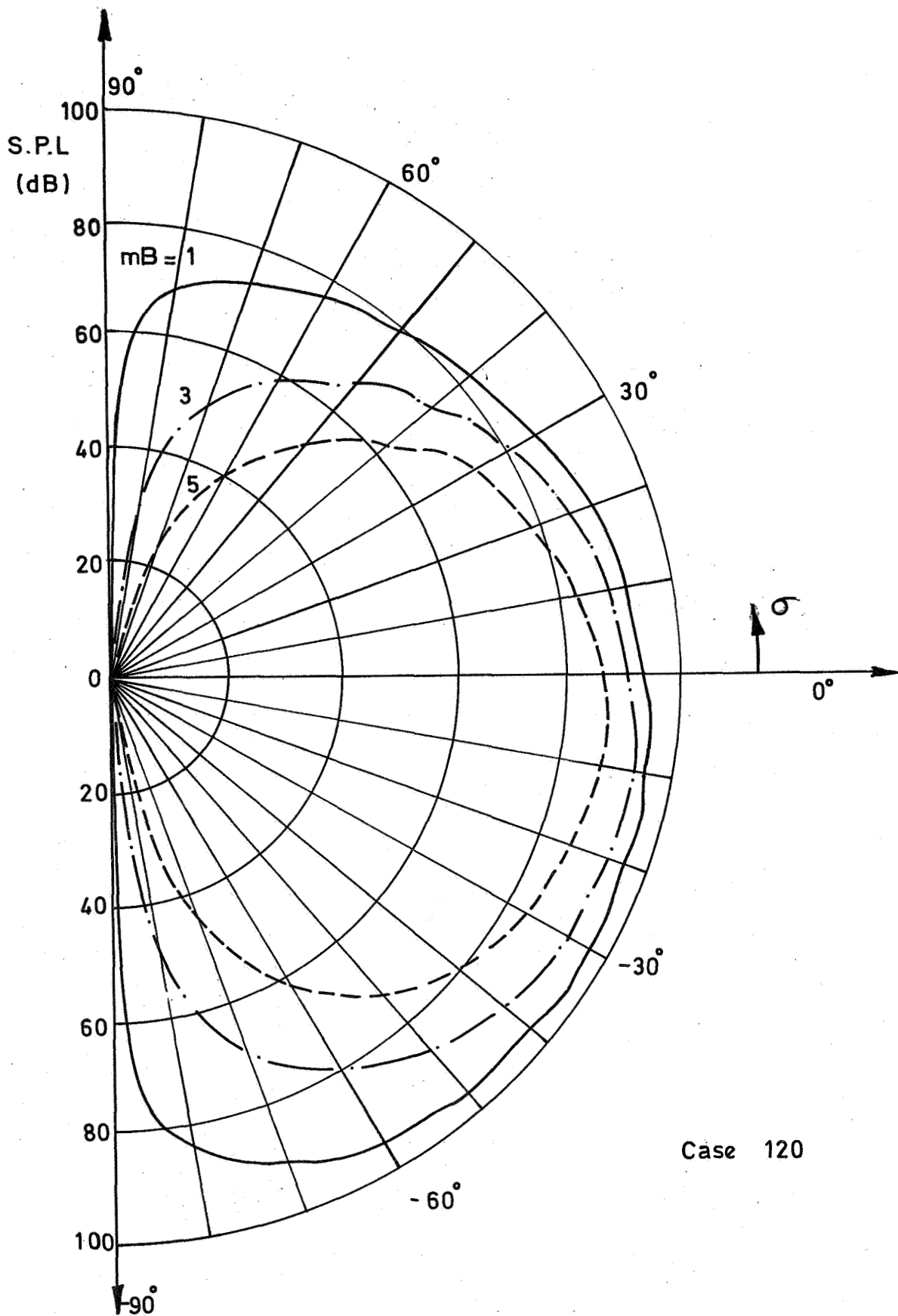


Fig. 1.1-10 Effect of force angle  $\beta = 24^\circ$  s = 0

Cases 101, 102, 103, 103A, 104.

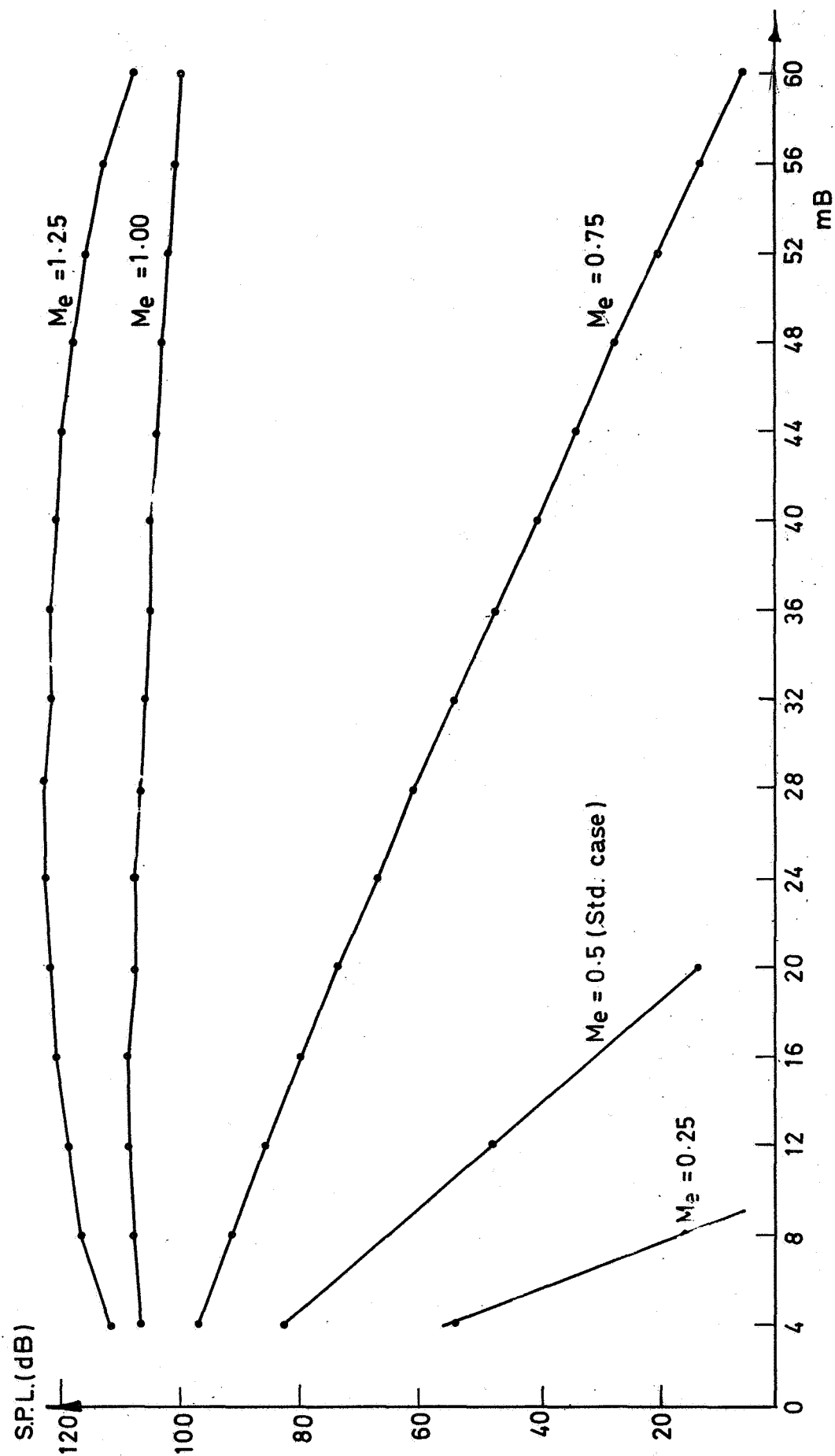


Fig.1.1.11 Effect of Mach no.  $\sigma = -30^\circ$ ,  $s = 0$

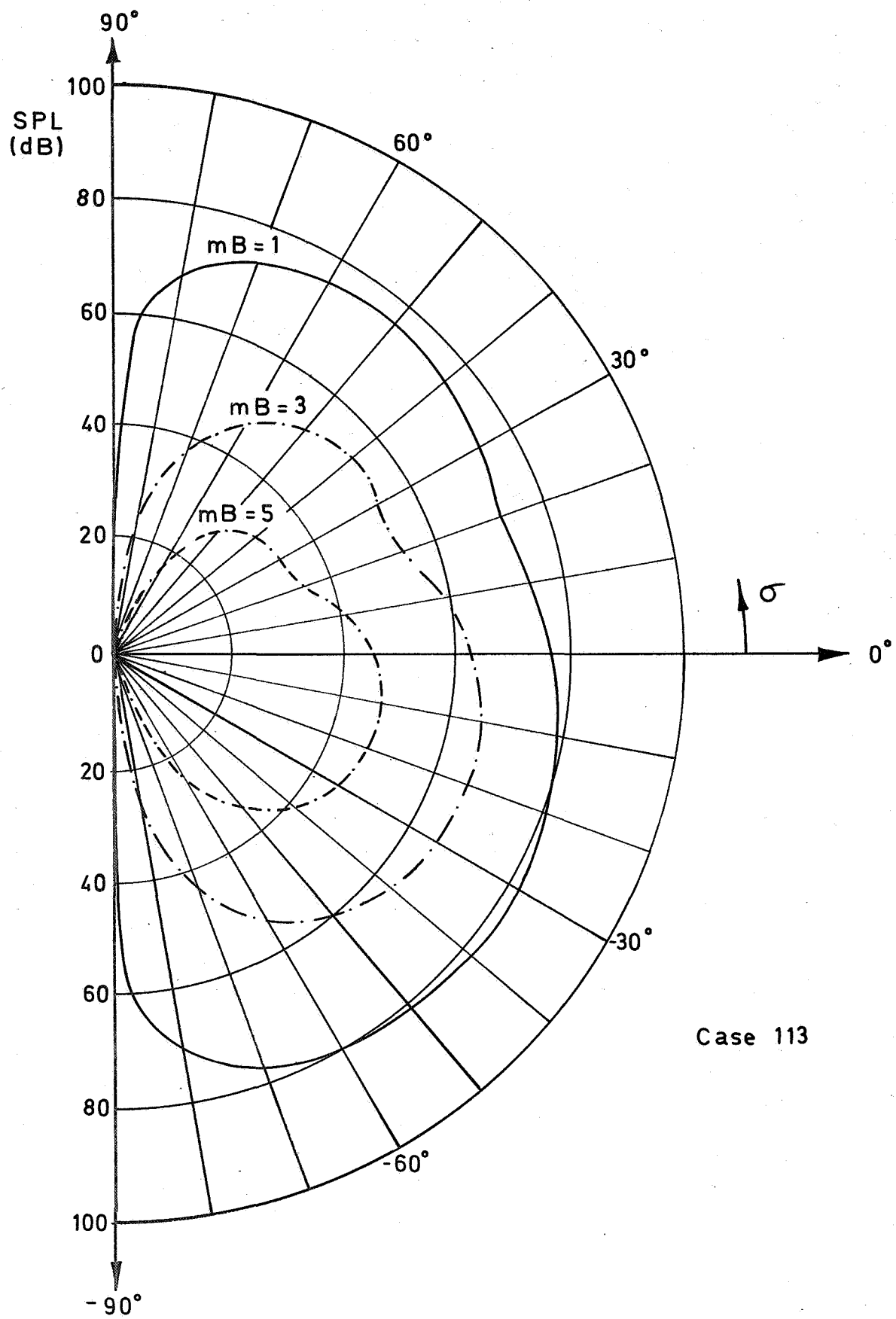
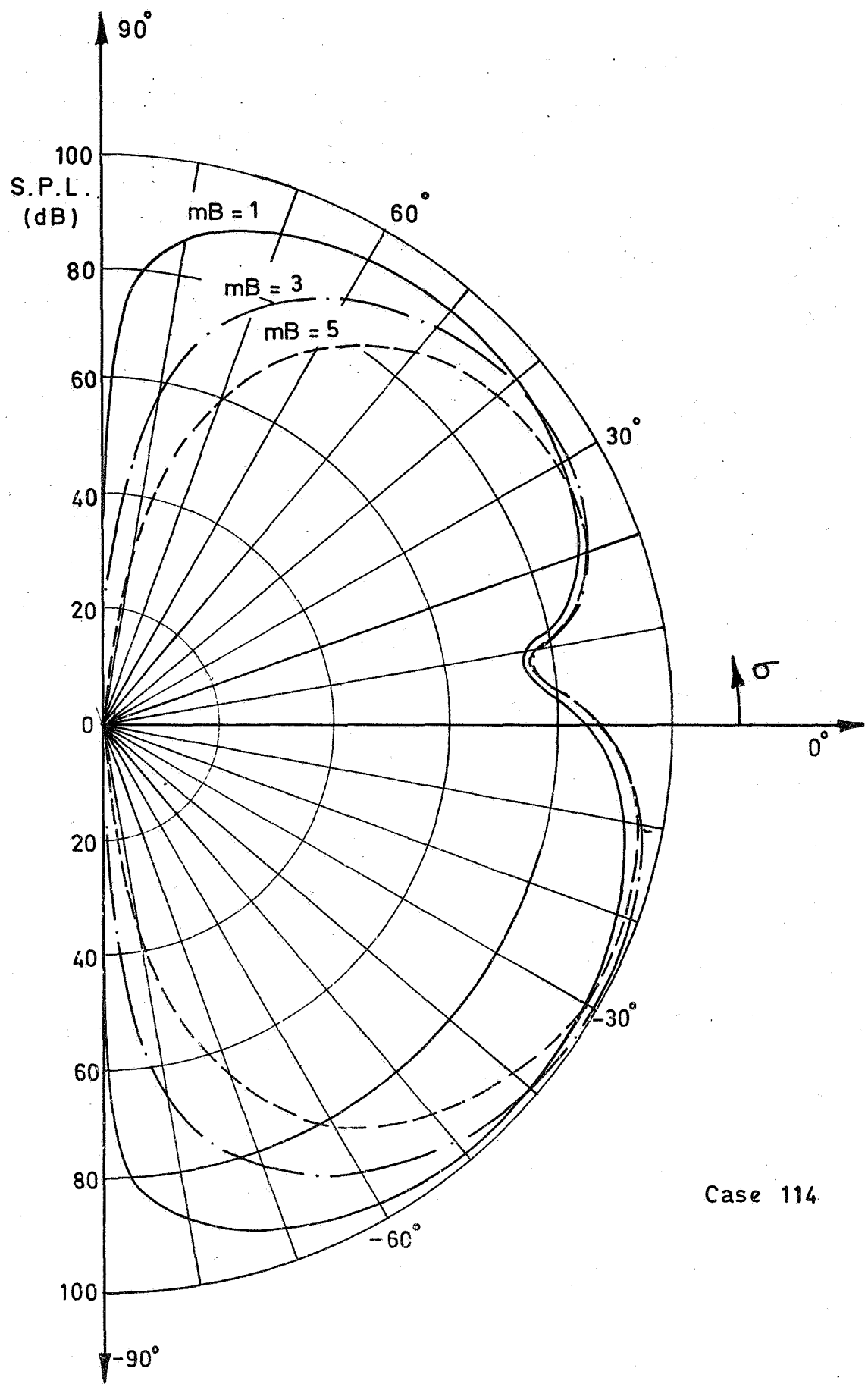


Fig.1.1:12 Effect of Mach no.  $M_e=25$ ,  $S=0$



Case 114

Fig. 1-1-13 Effect of Mach no.  $M_0 = 0.75$   $S = 0$

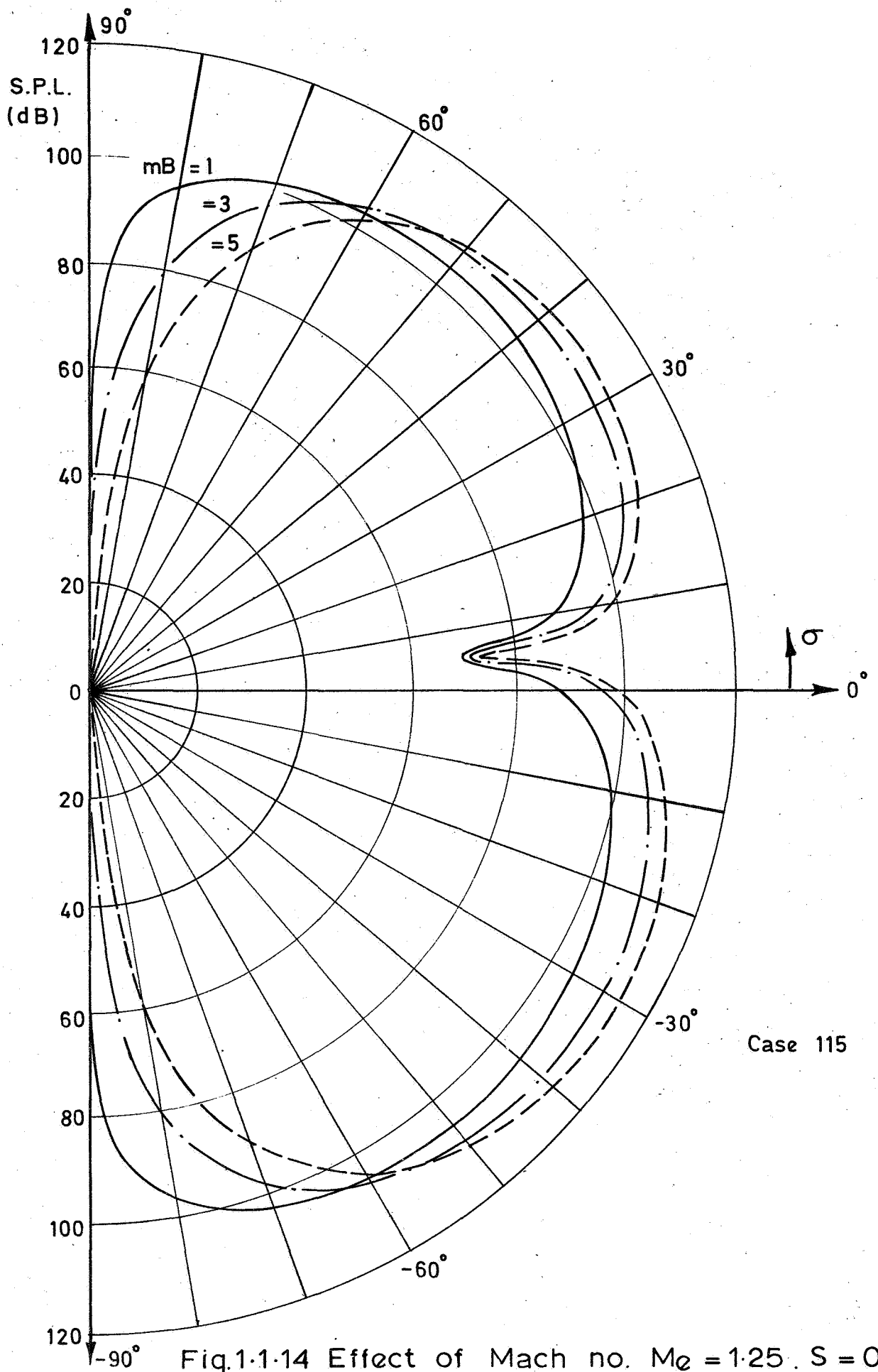


Fig.1-1-14 Effect of Mach no.  $M_0 = 1.25$ .  $S = 0$

Case 125, 125A, 126, 127, 121.

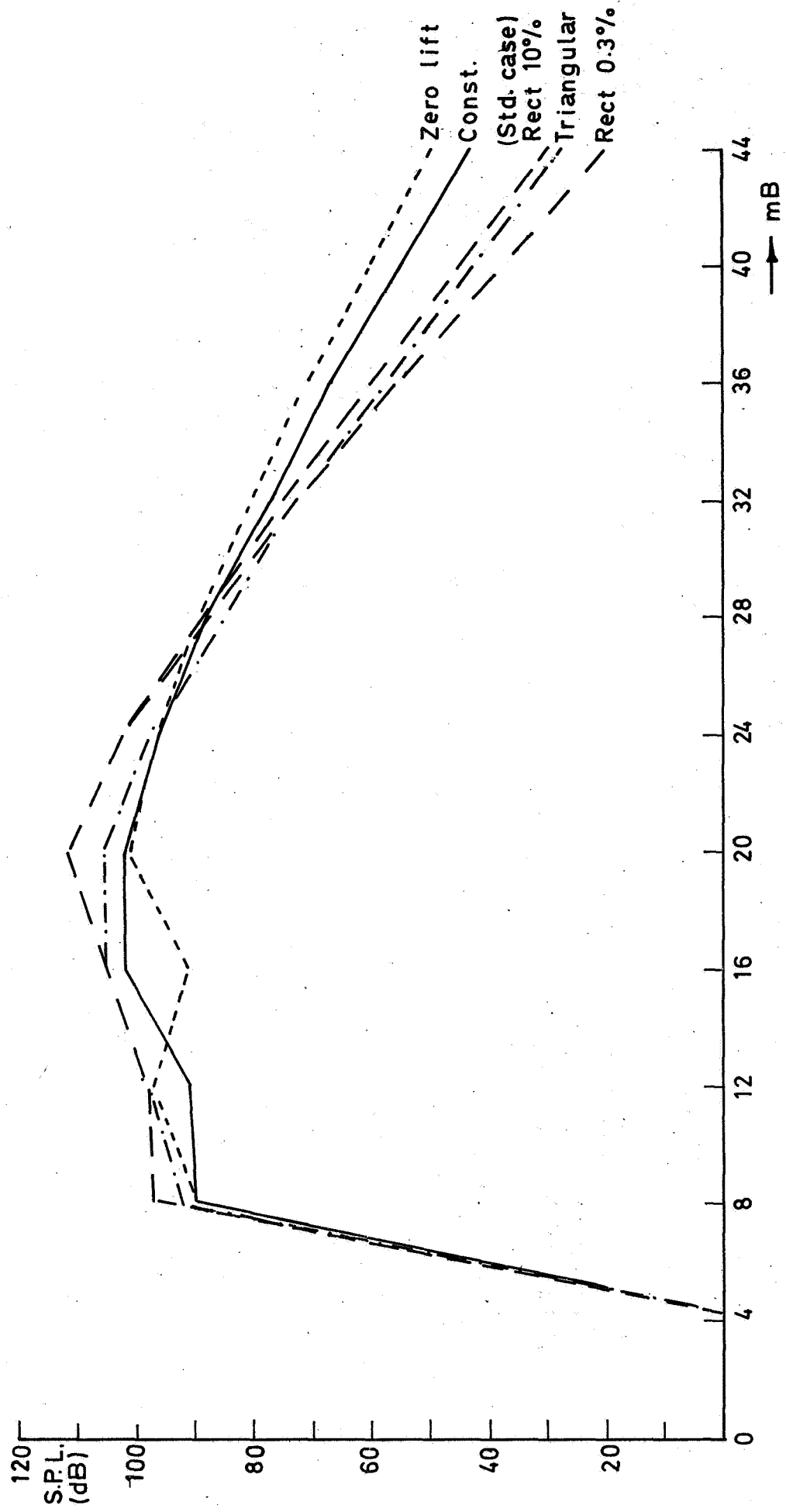


Fig. 1.1.15 Effect of span distribution  $\sigma = -30^\circ$   $s = 12$

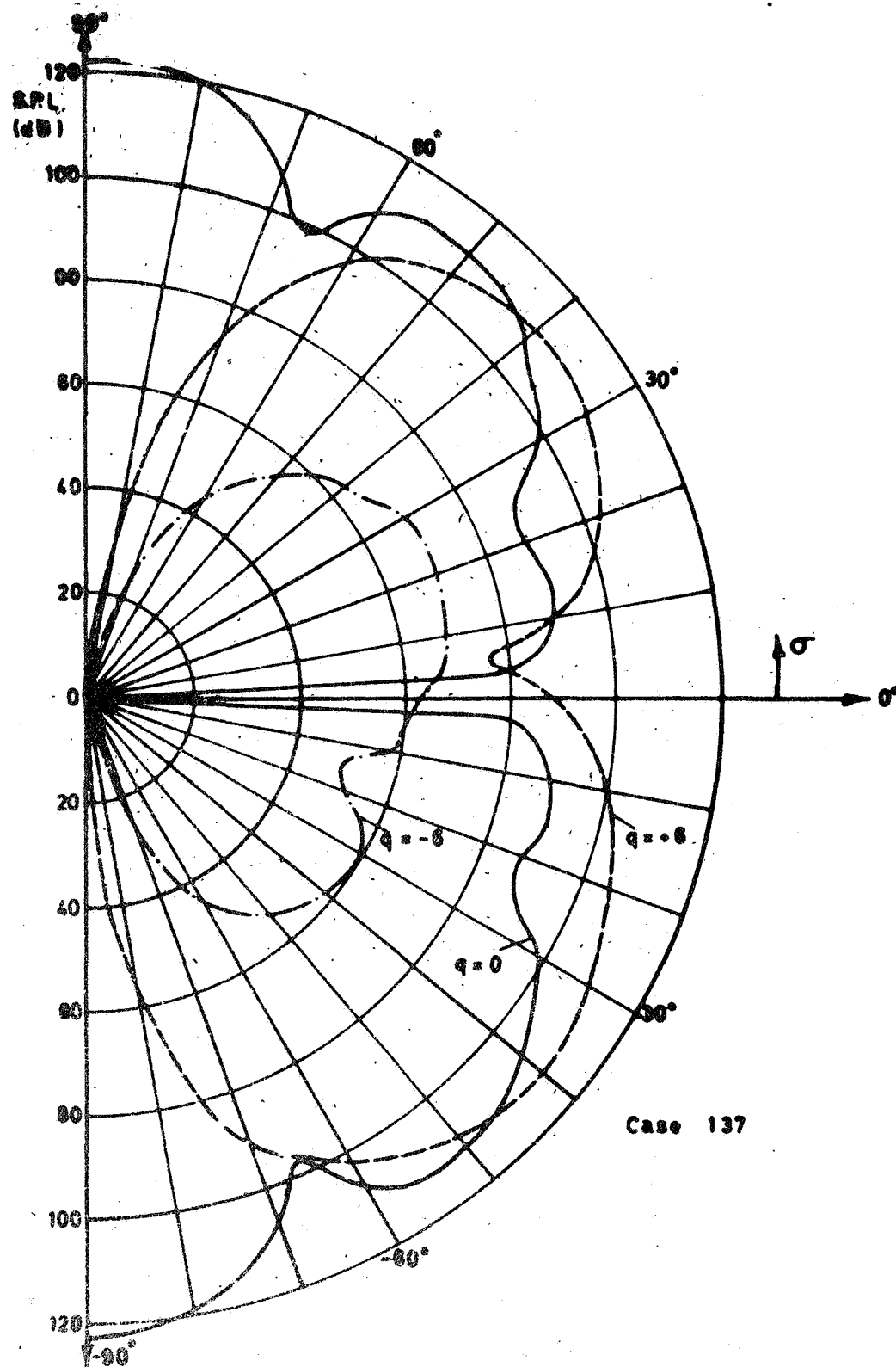
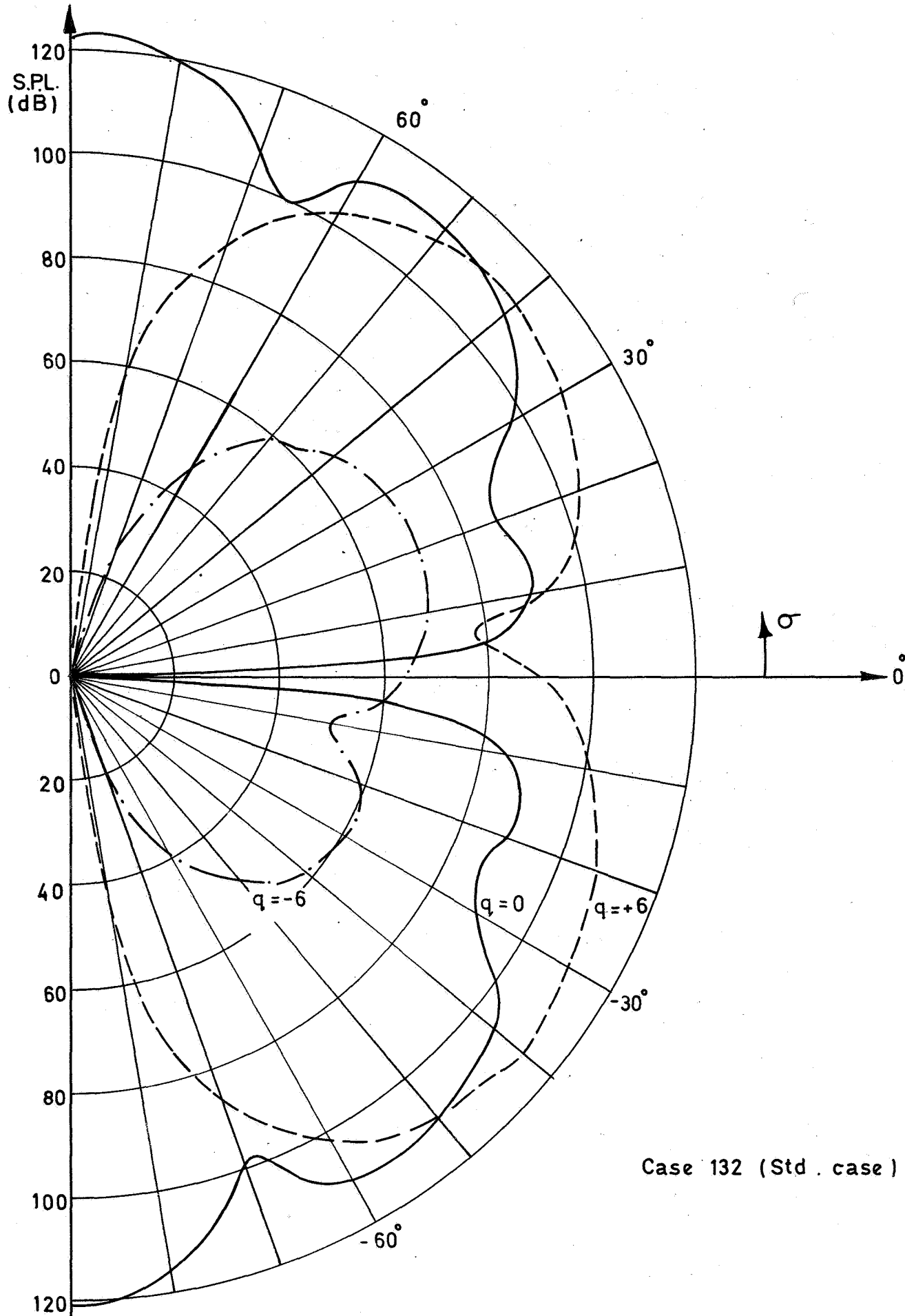


Fig. 11-16 Effect of span distribution 0.3%.  $S = 12$



Case 132 (Std. case)

Fig.1.1-17 Effect of distribution 10% (std. case)  $S = 12$

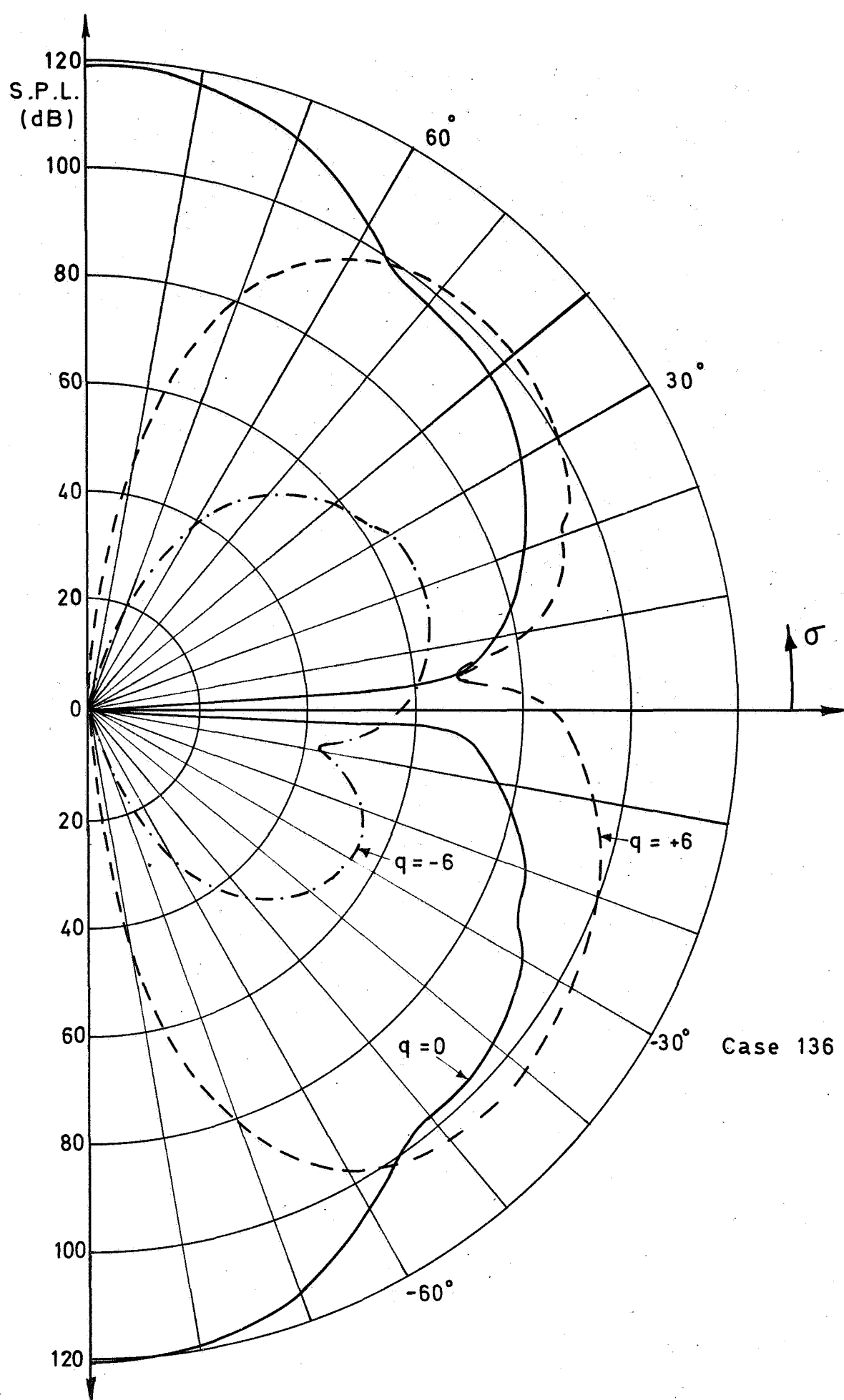


Fig. 1-1-18 Effect of span distribution, Constant  $S = 12$ .

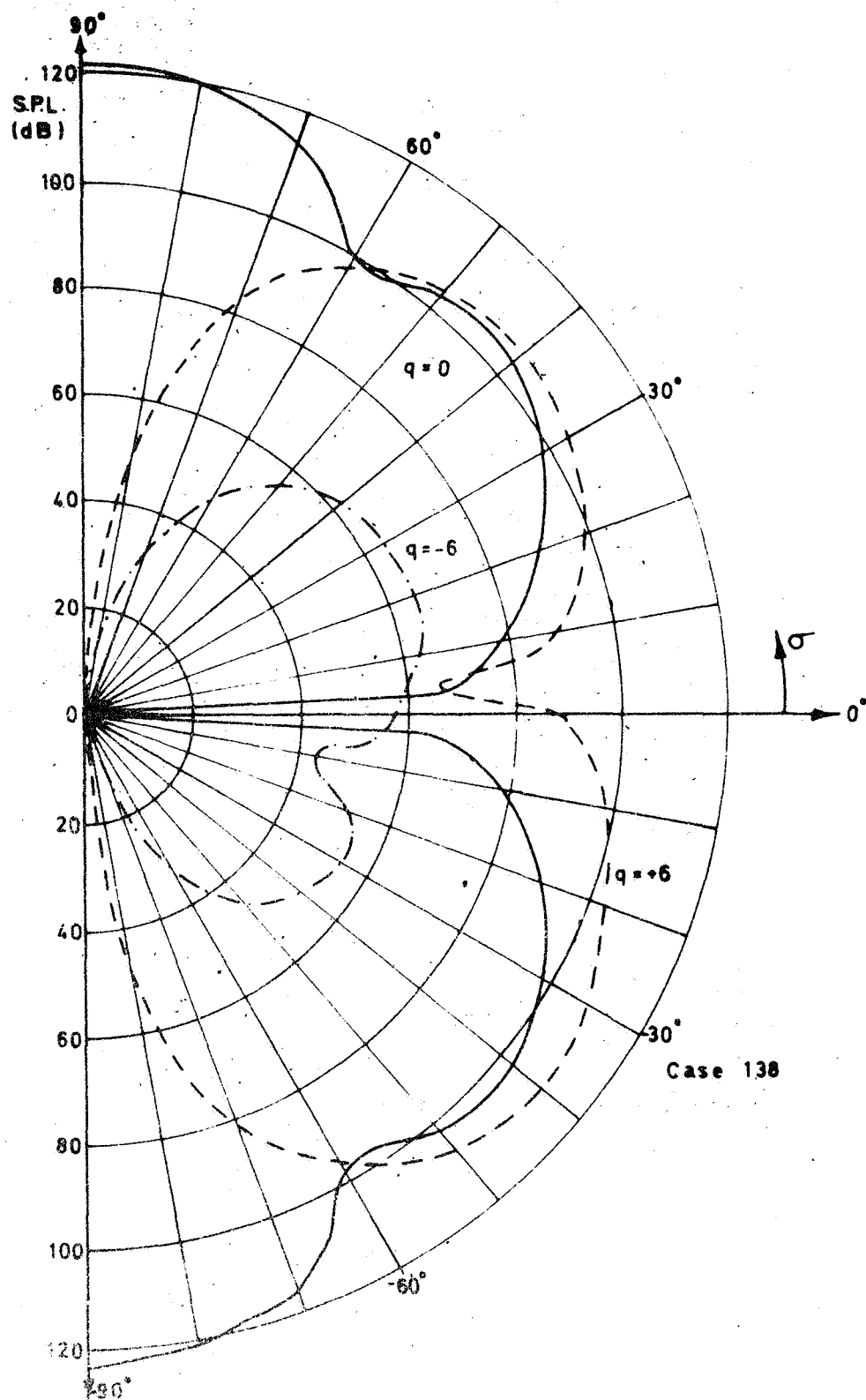


Fig 14-19 Effect of span distribution Triangular  $S=12$

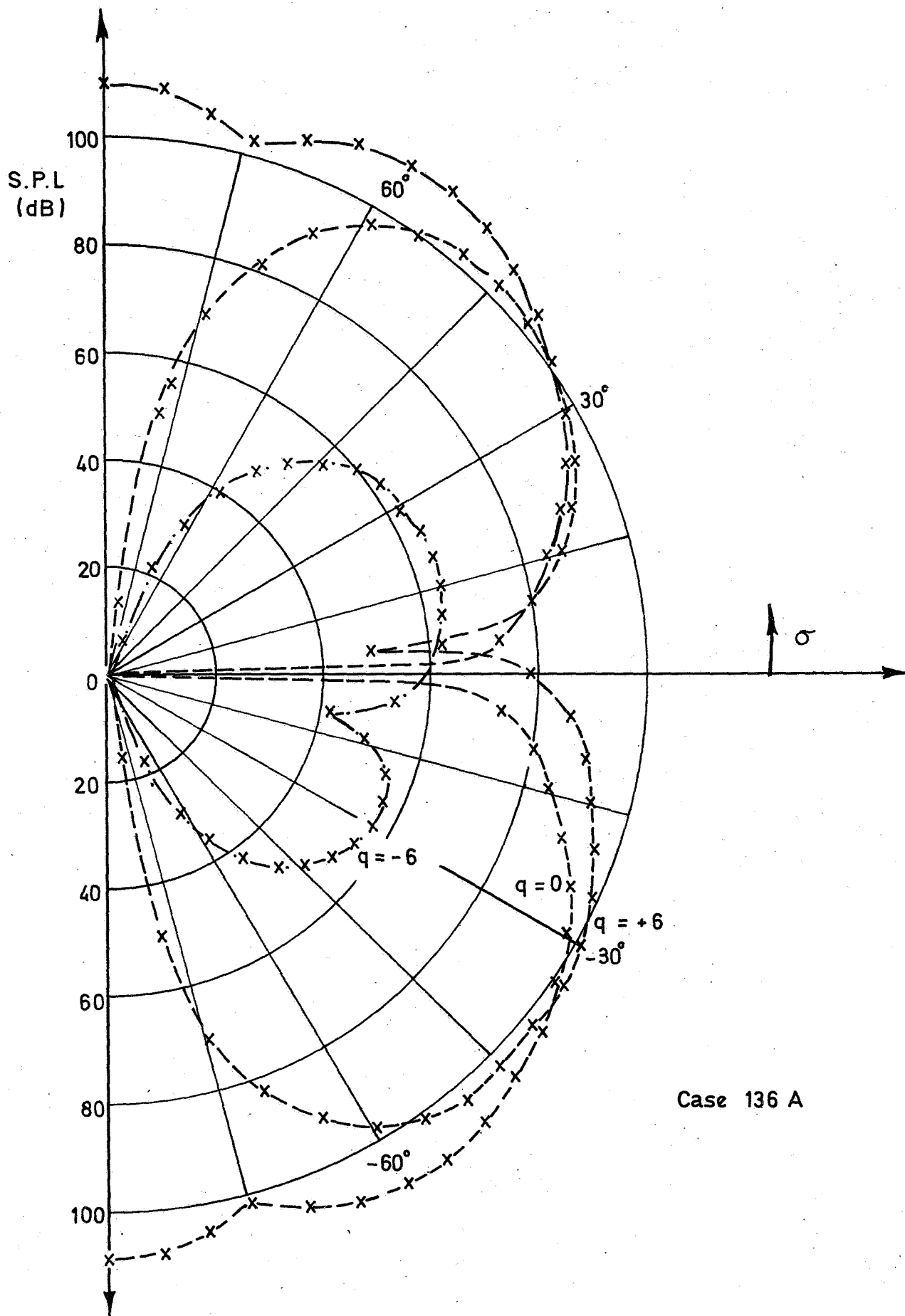


Fig.1.1-20 Effect of distribution, zero lift  $S=12$ .

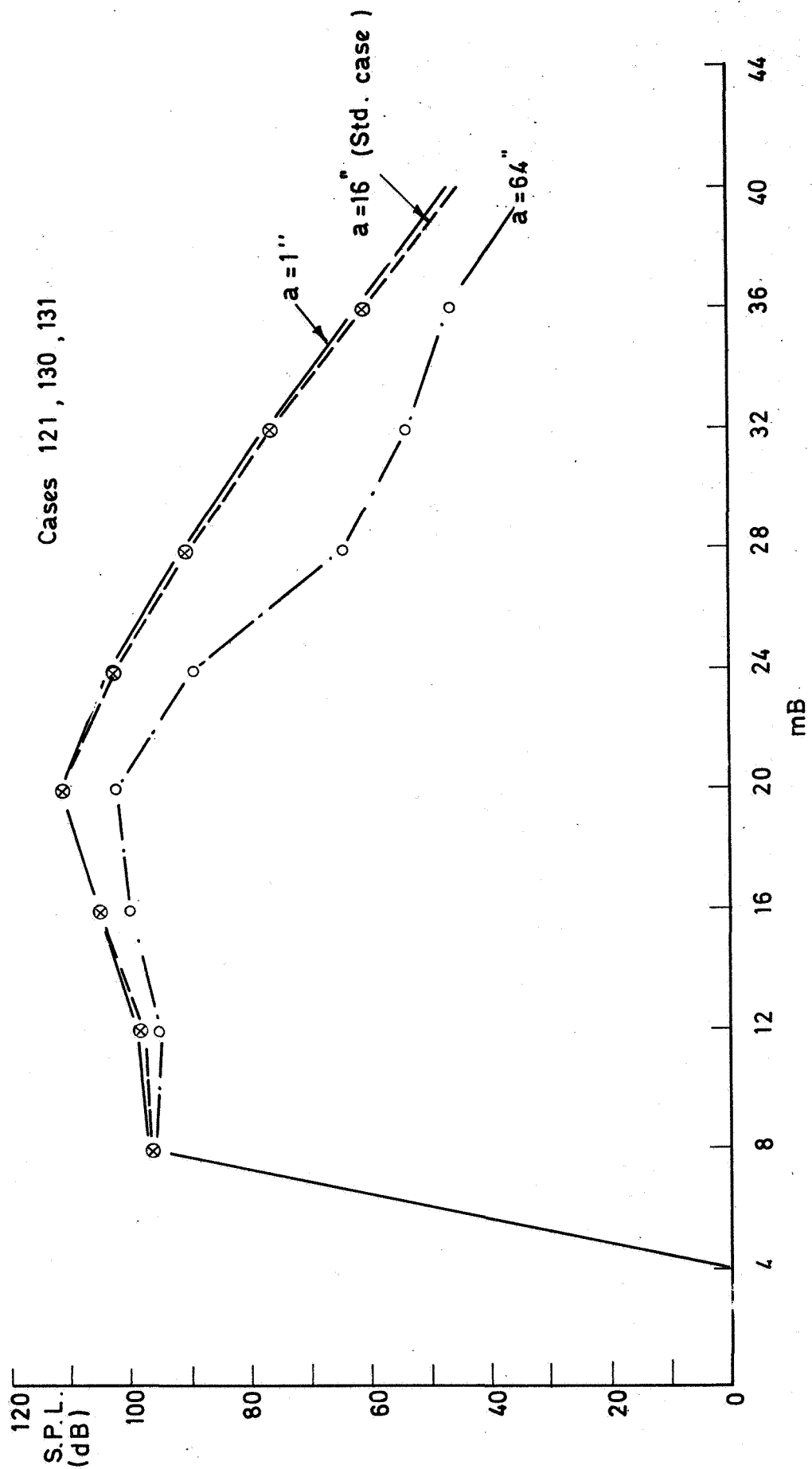


Fig.1.1.21 Effect of chord width  $s = 12$   $\sigma = -30^\circ$

Cases 121, 128, 129.

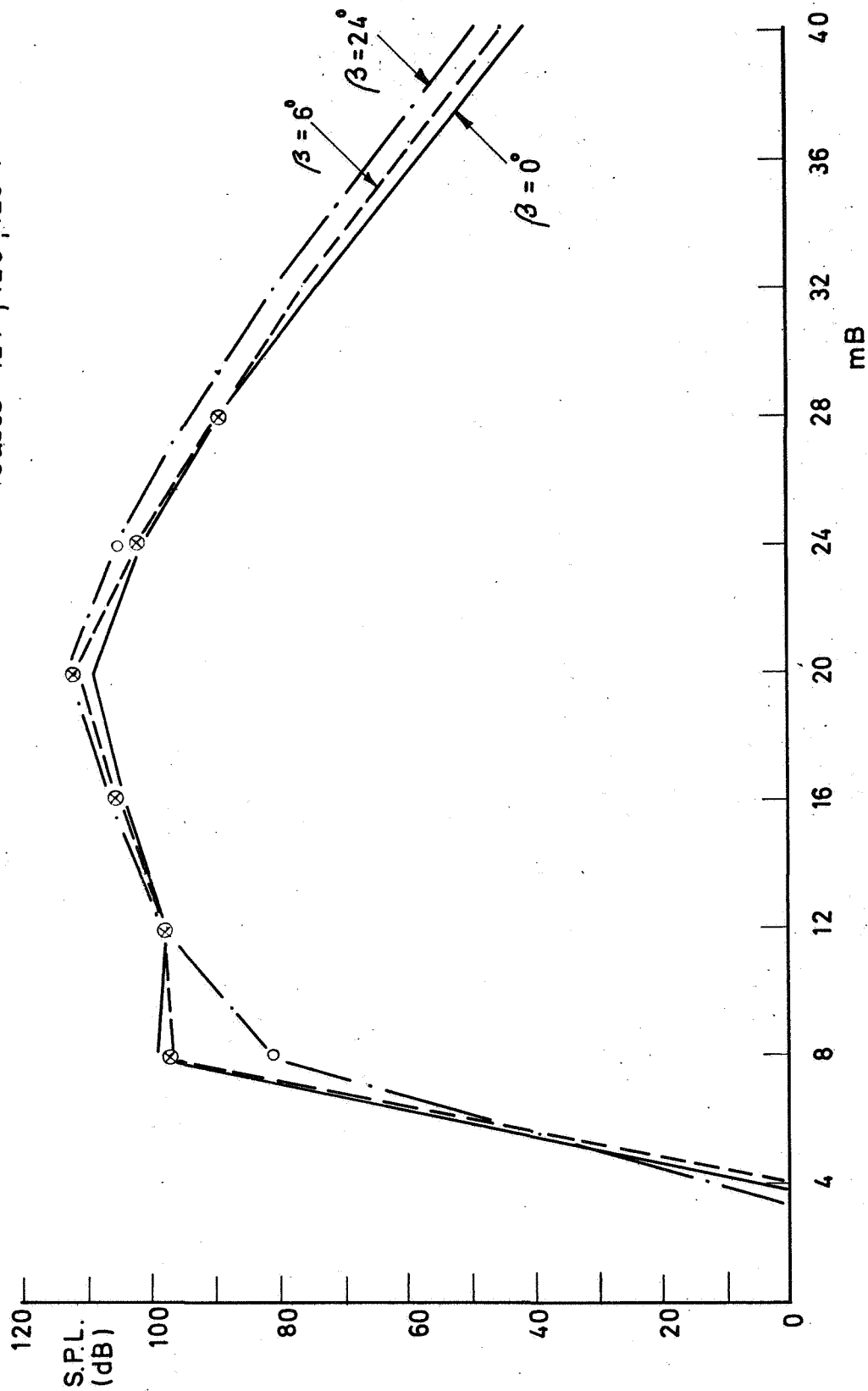


Fig.1.1-22 Effect of force angle.  $\sigma = -30^\circ$   $s = 12$ .

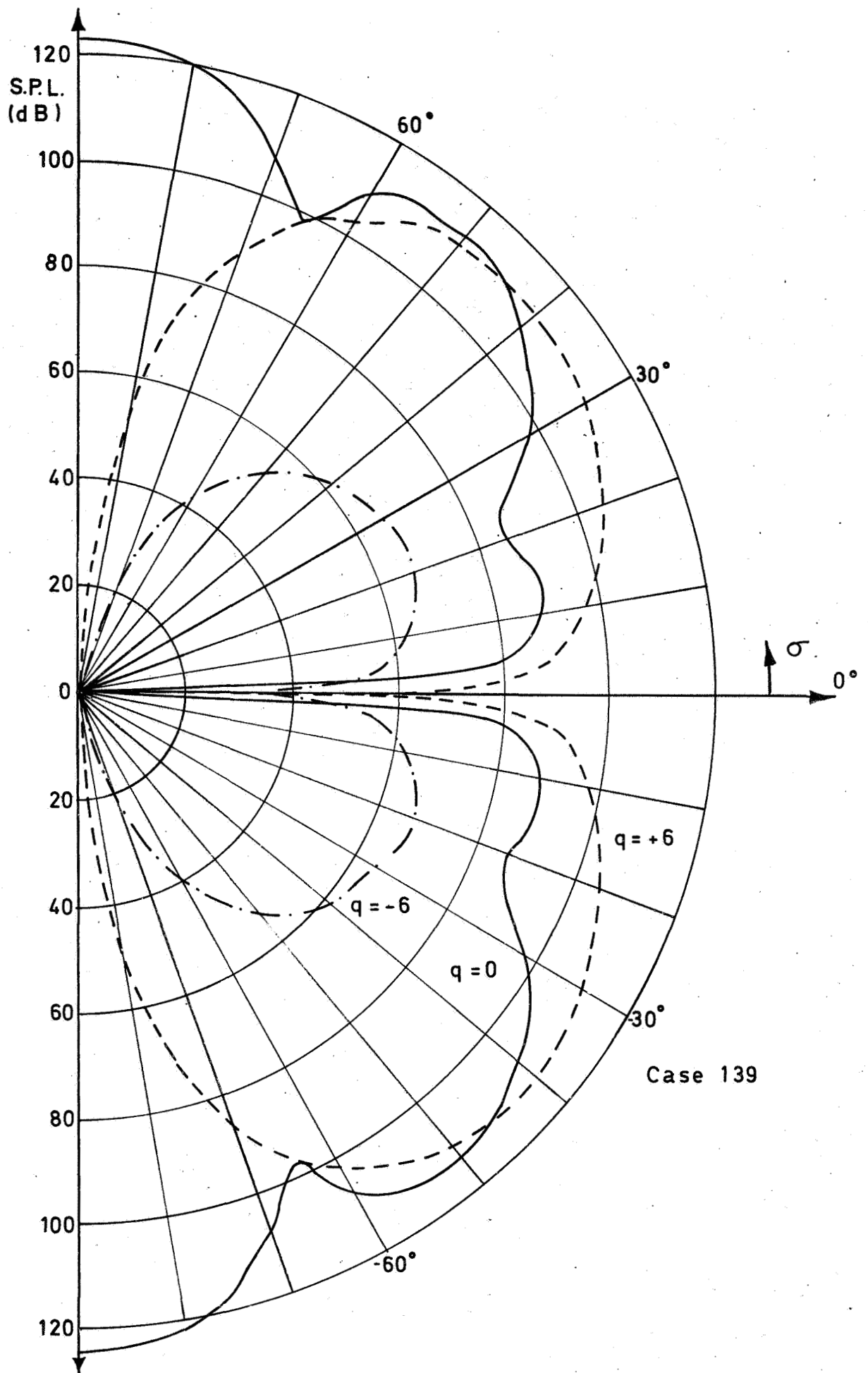


Fig.1-1-23 Effect of force angle  $\beta = 0^\circ$   $S = 12$ .

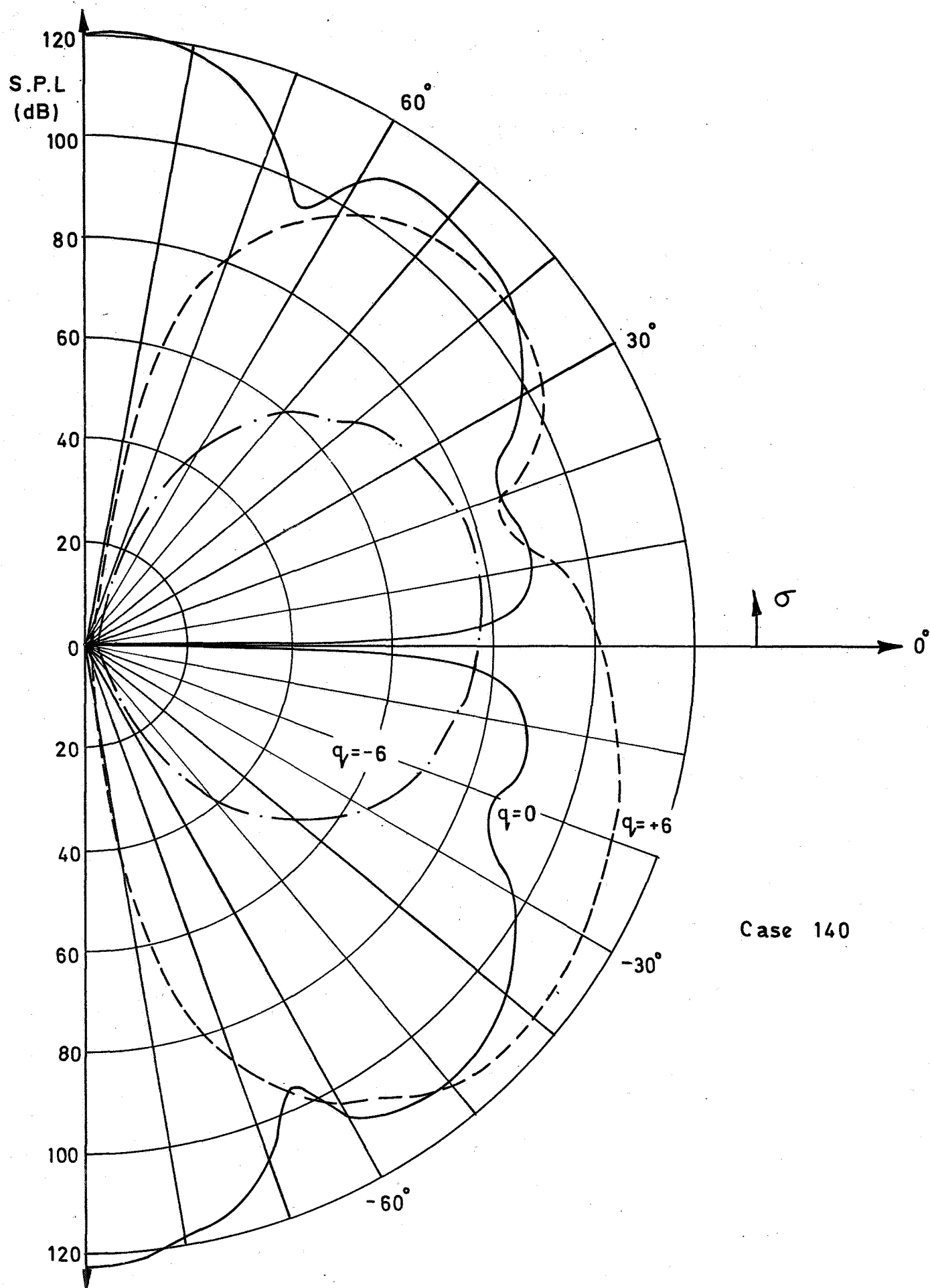


Fig.1.1-24 Effect of force angle .  $\beta = 24^\circ$  .  $s = 12$  .

Case 121, 122, 123, 123A, 124

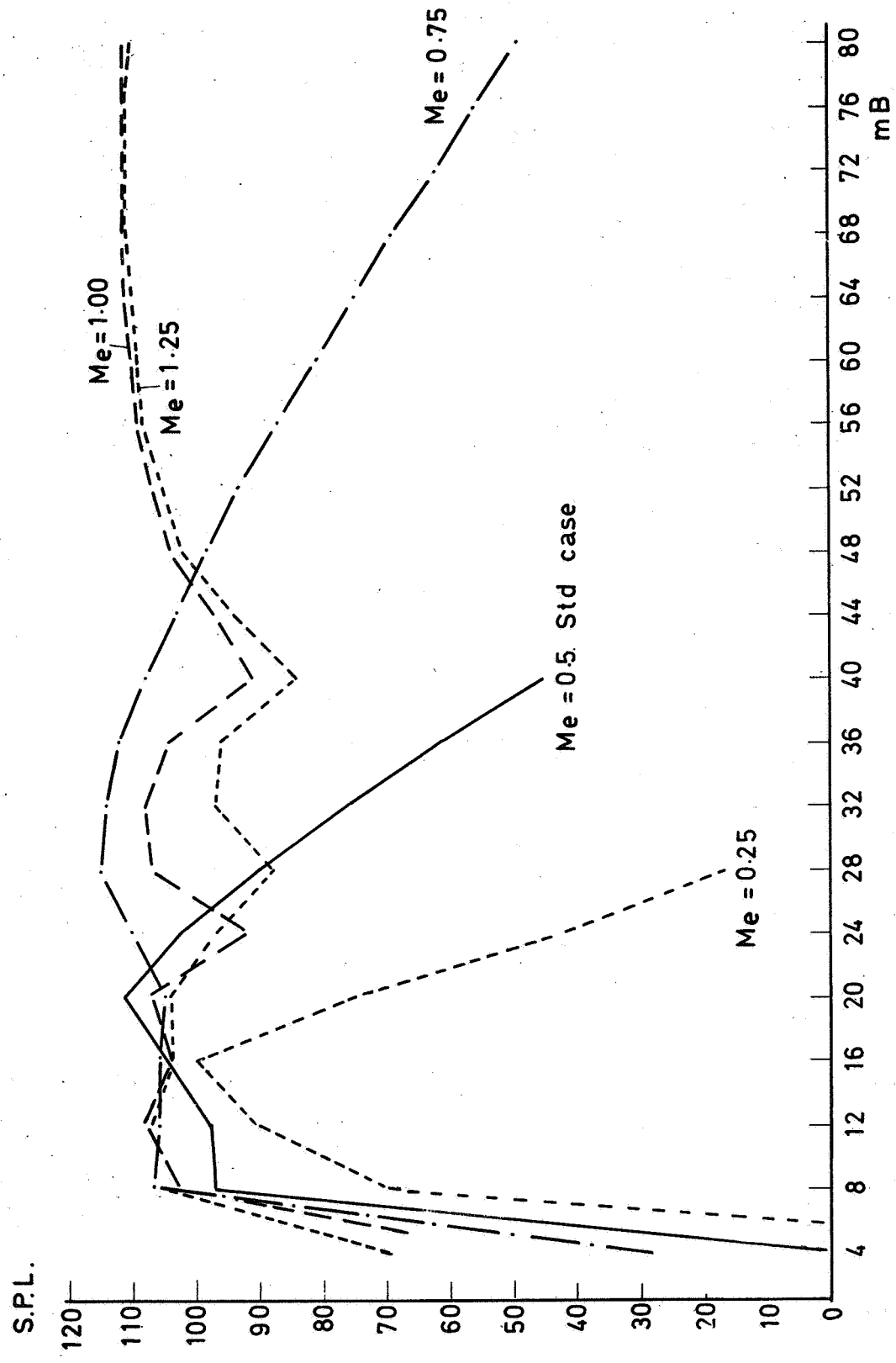


Fig.1.1.25 Effect of Mach number  $\sigma = -30^\circ$ ,  $S = 12$

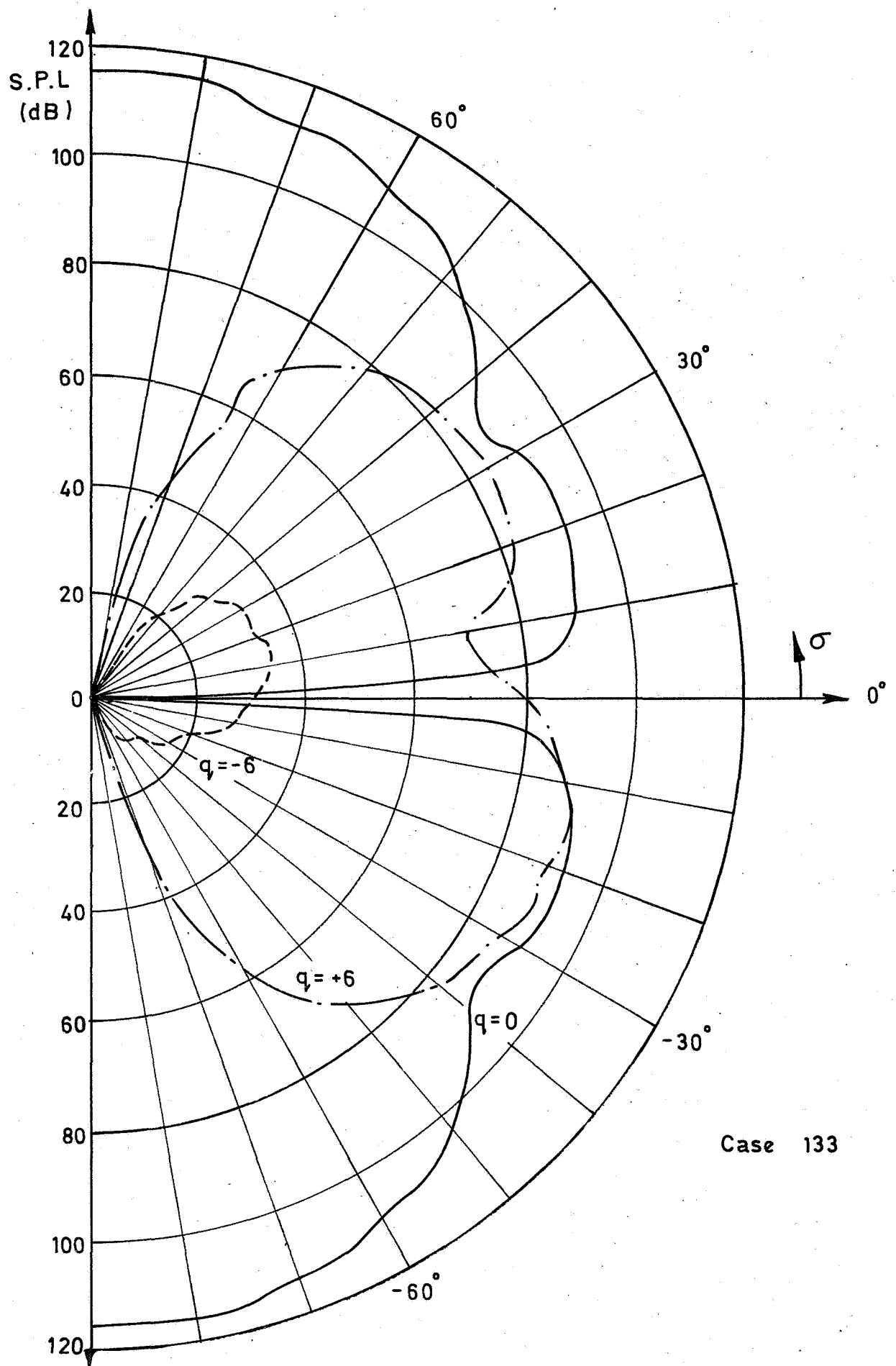


Fig.1-1-26 Effect of Mach no.  $Me = 0.25$ ,  $S = 12$ .

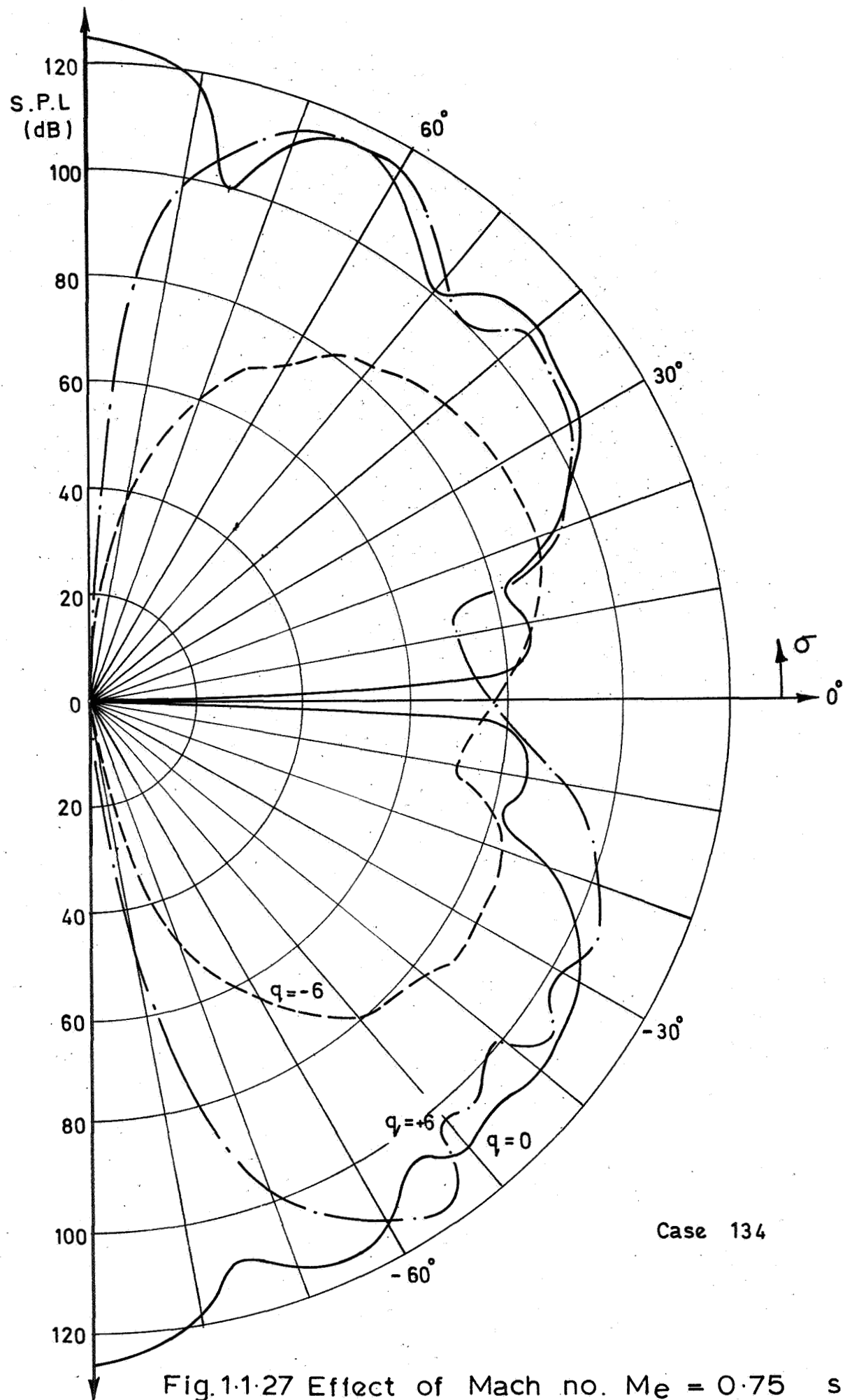


Fig.1.1.27 Effect of Mach no.  $Me = 0.75$   $s = 12$ .

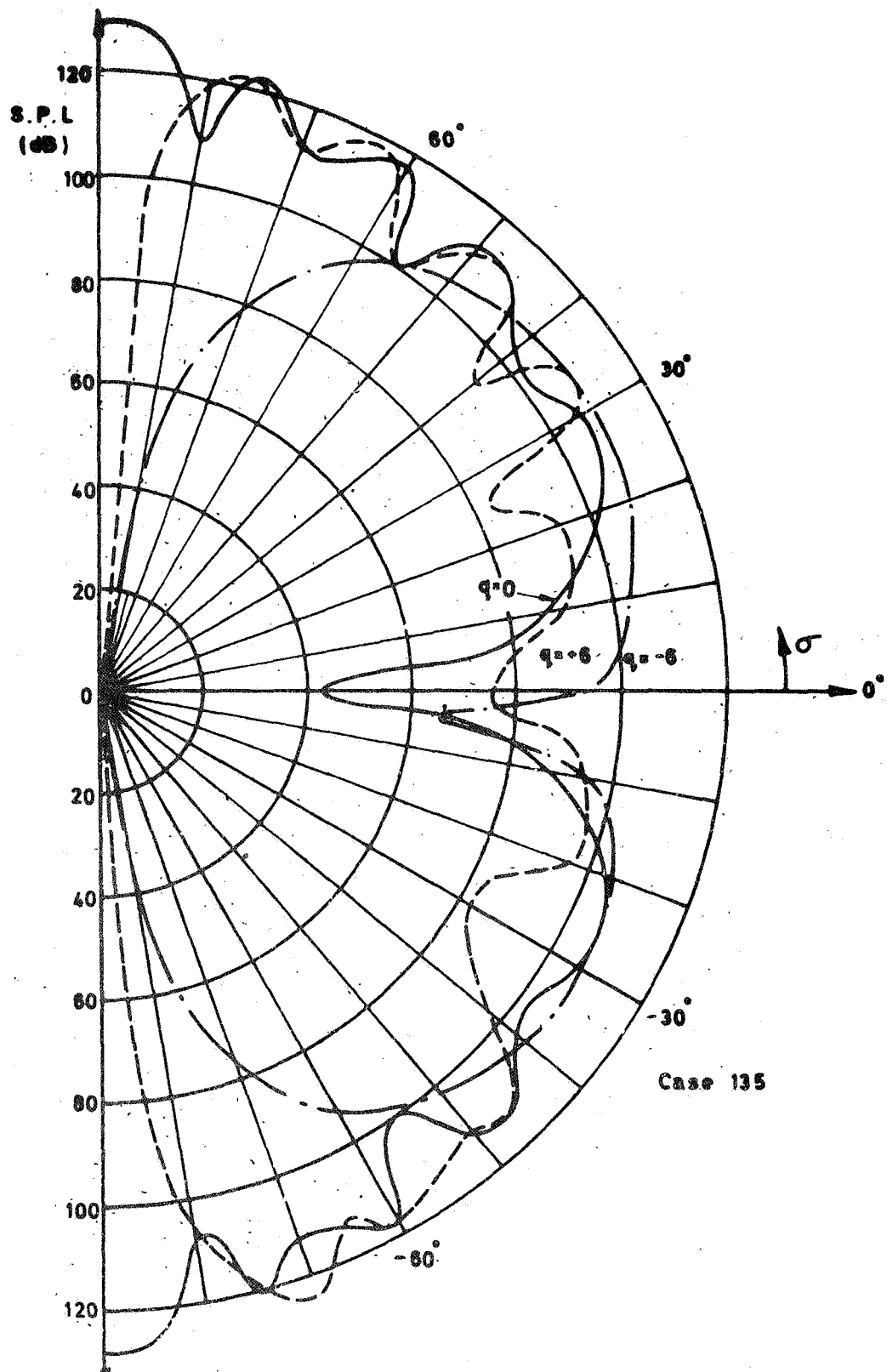


Fig.1-1-28 Effect of Mach no.  $Me = 1.25$ ,  $S = 12$ .

Case 141, 145, 146, 147, 145A

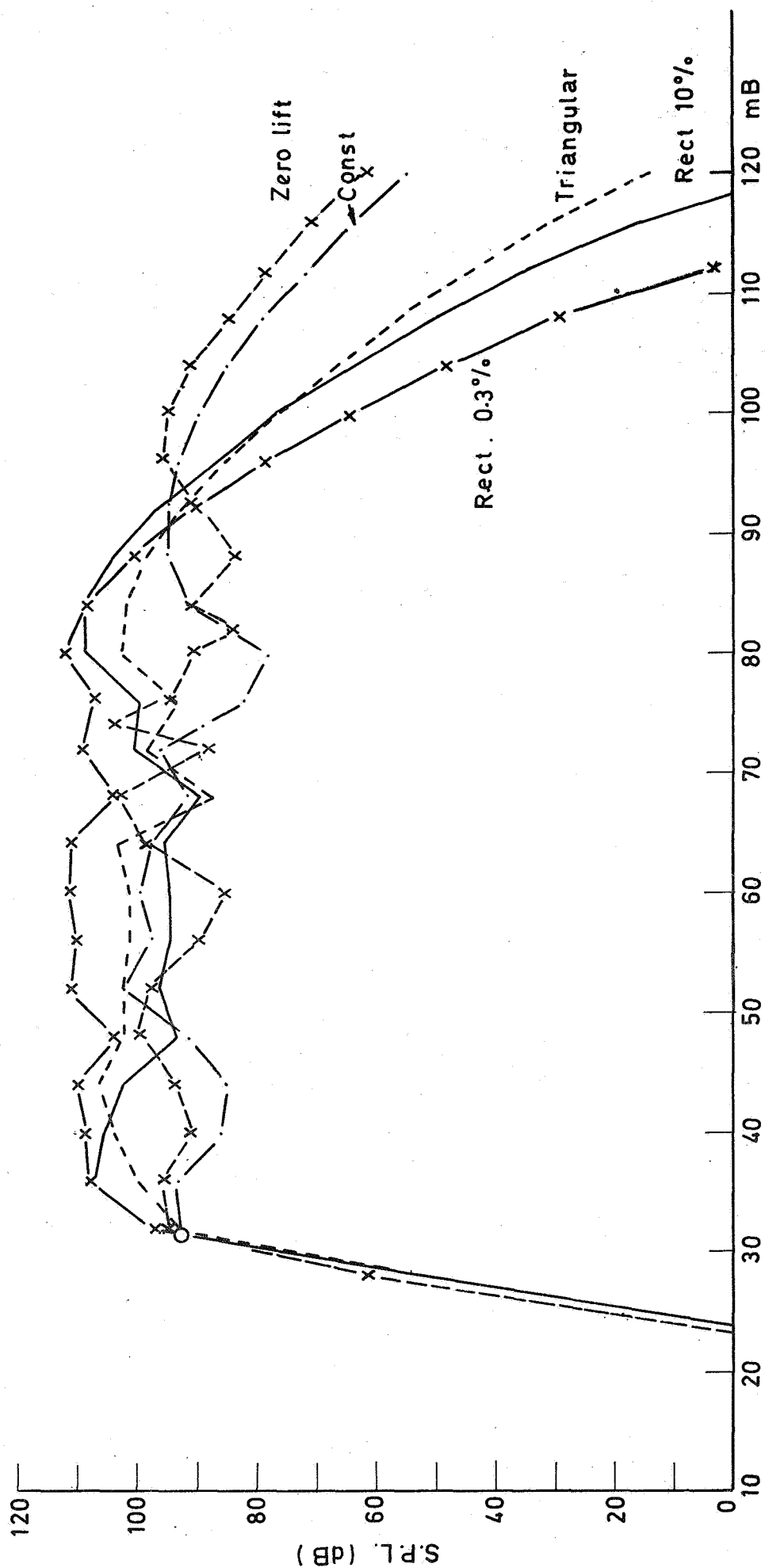
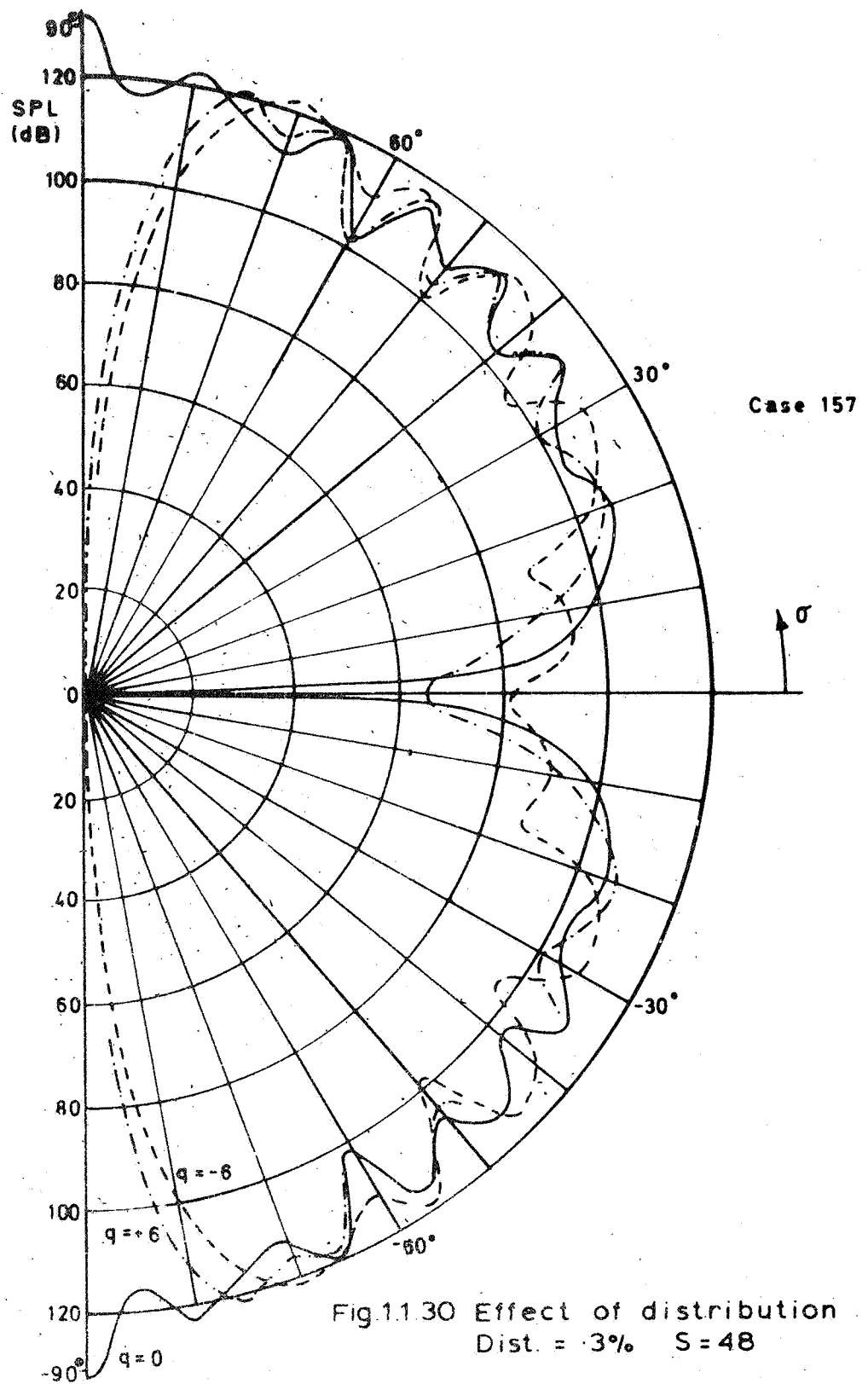
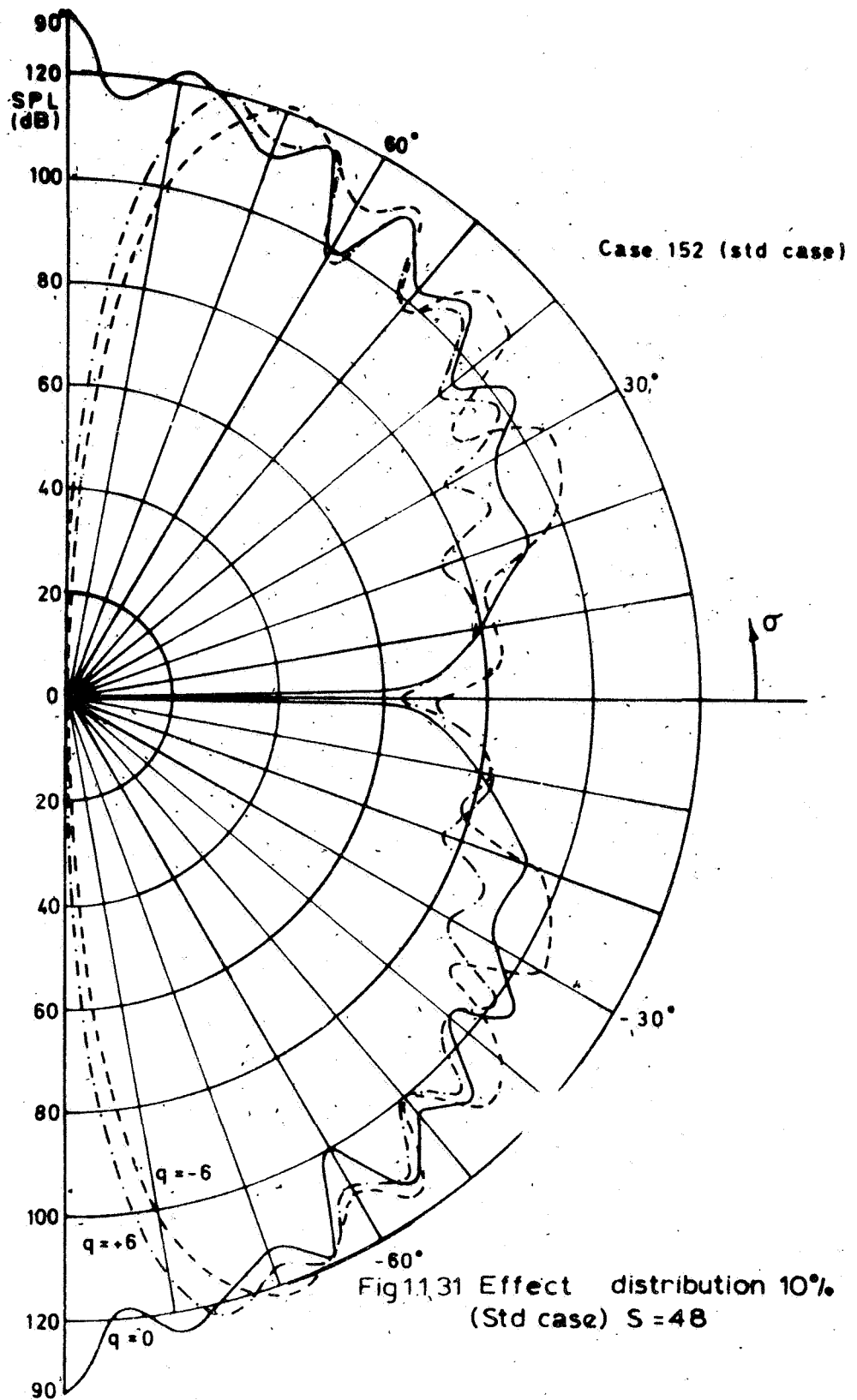
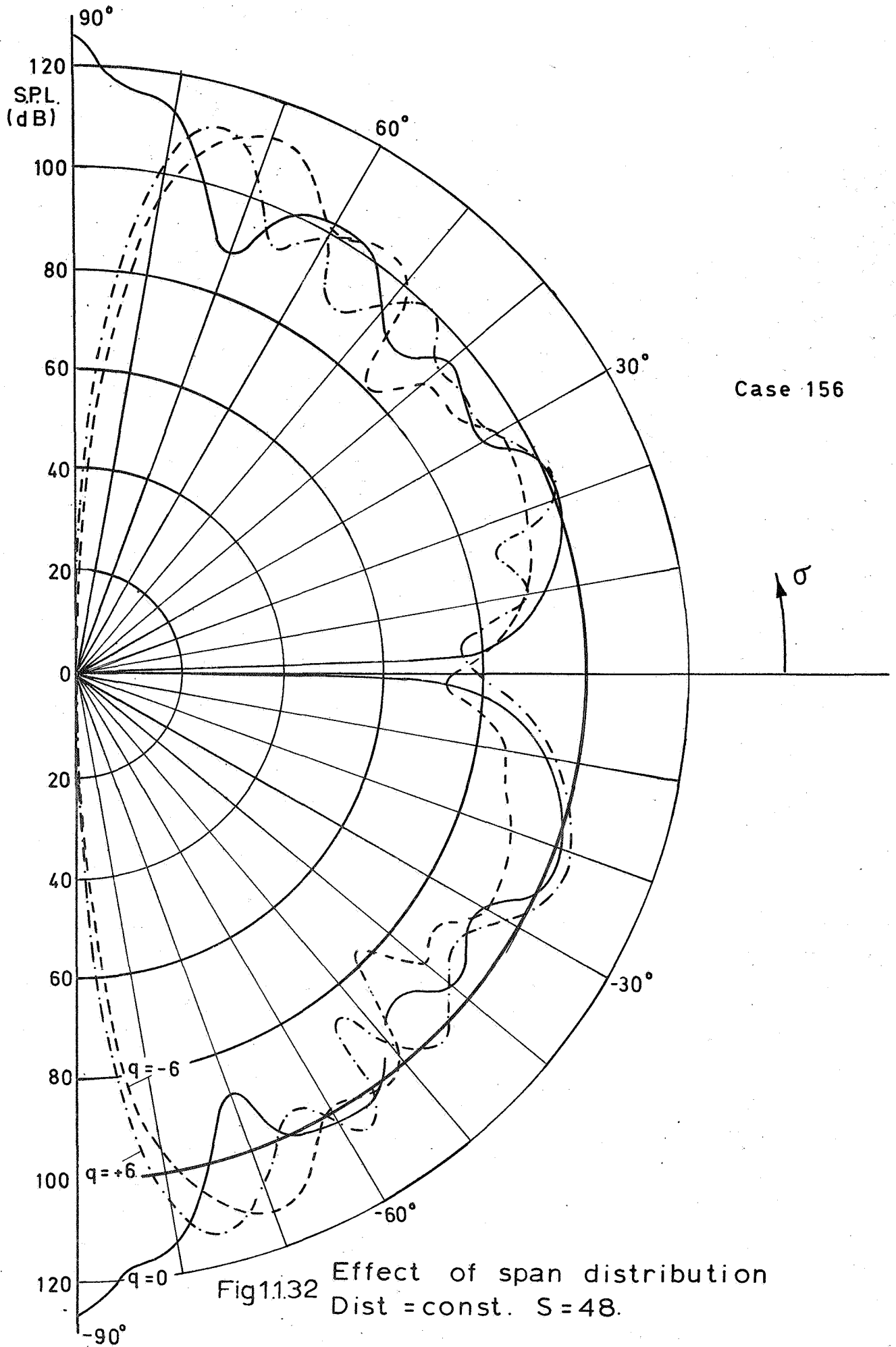
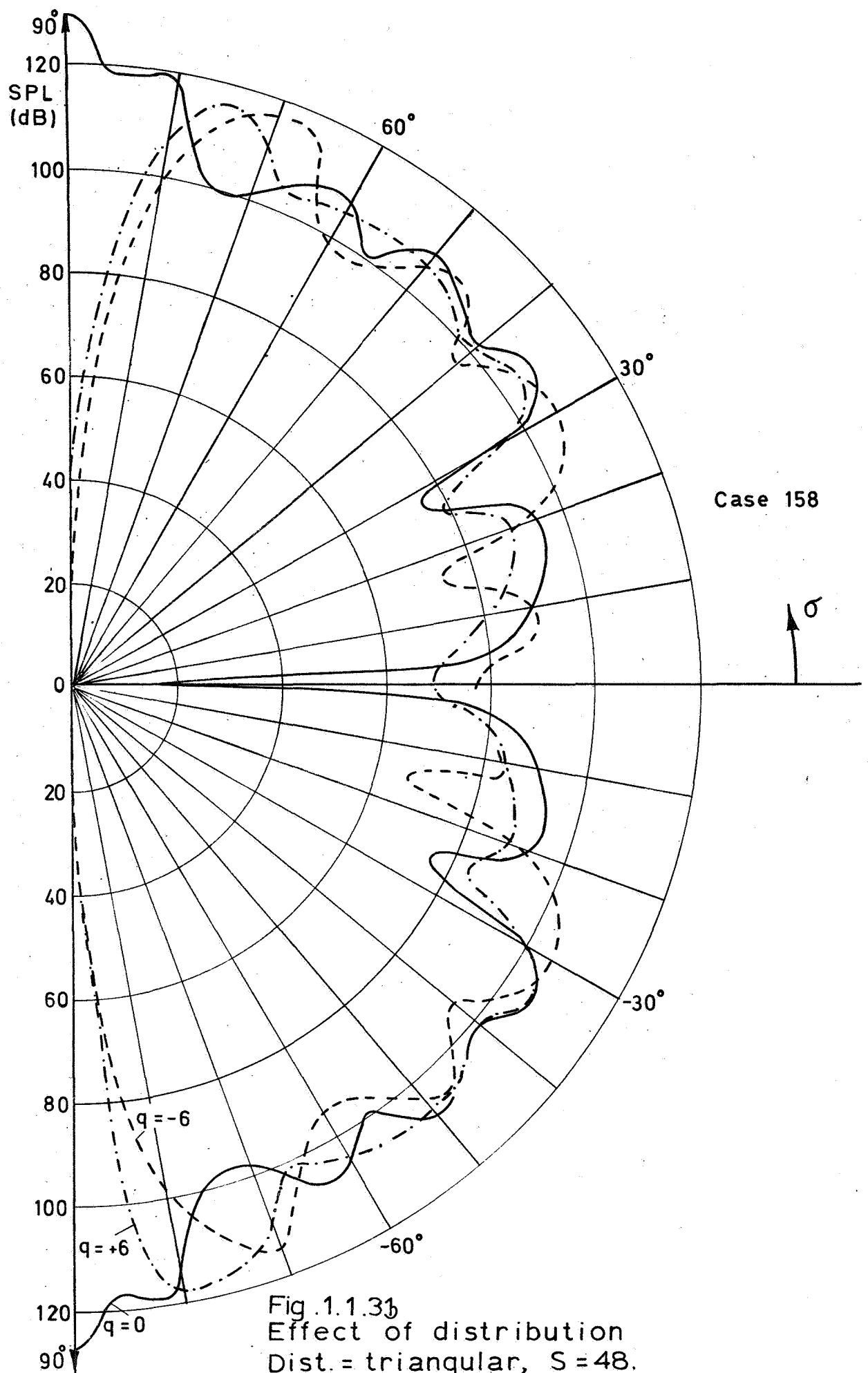


Fig.1.1.29 Effect of distribution  $S=48$   $\sigma=-30^\circ$









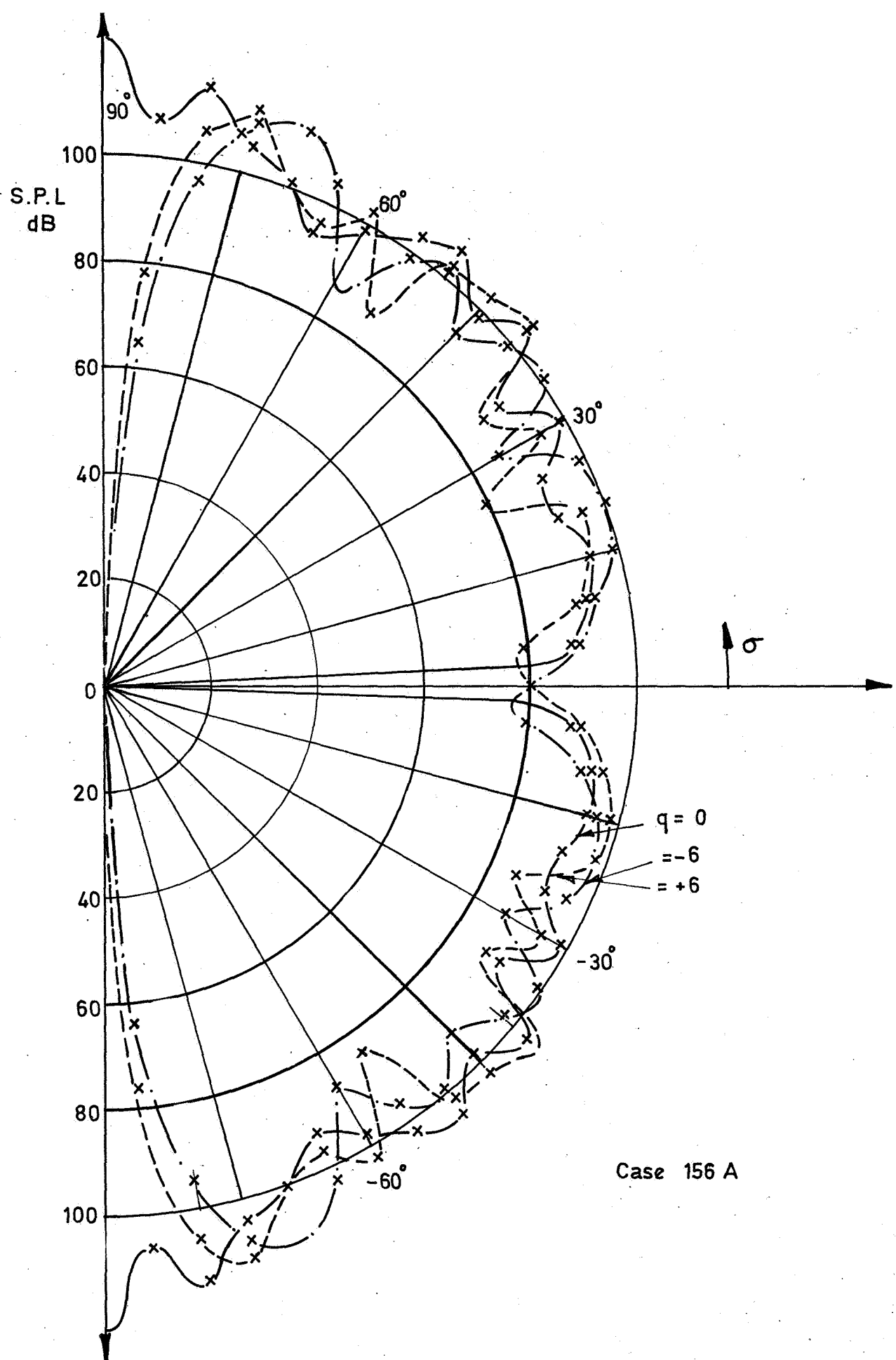


Fig.11.34 Effect of distribution, zero lift,  $S = 48$

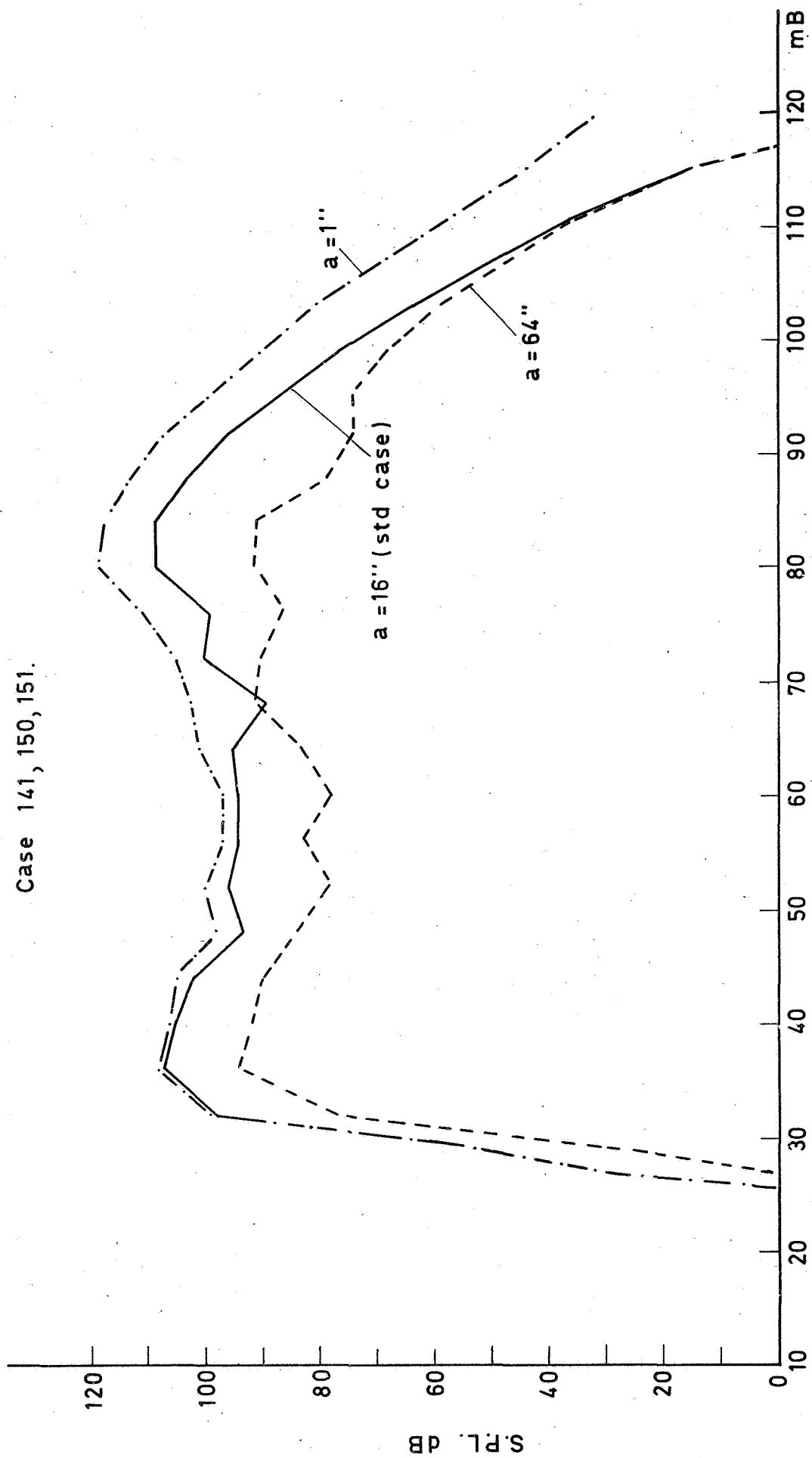


Fig. 1.1.35 Effect of chord width  $S=48$ ,  $\sigma=-30^\circ$

Case 141, 148, 149.

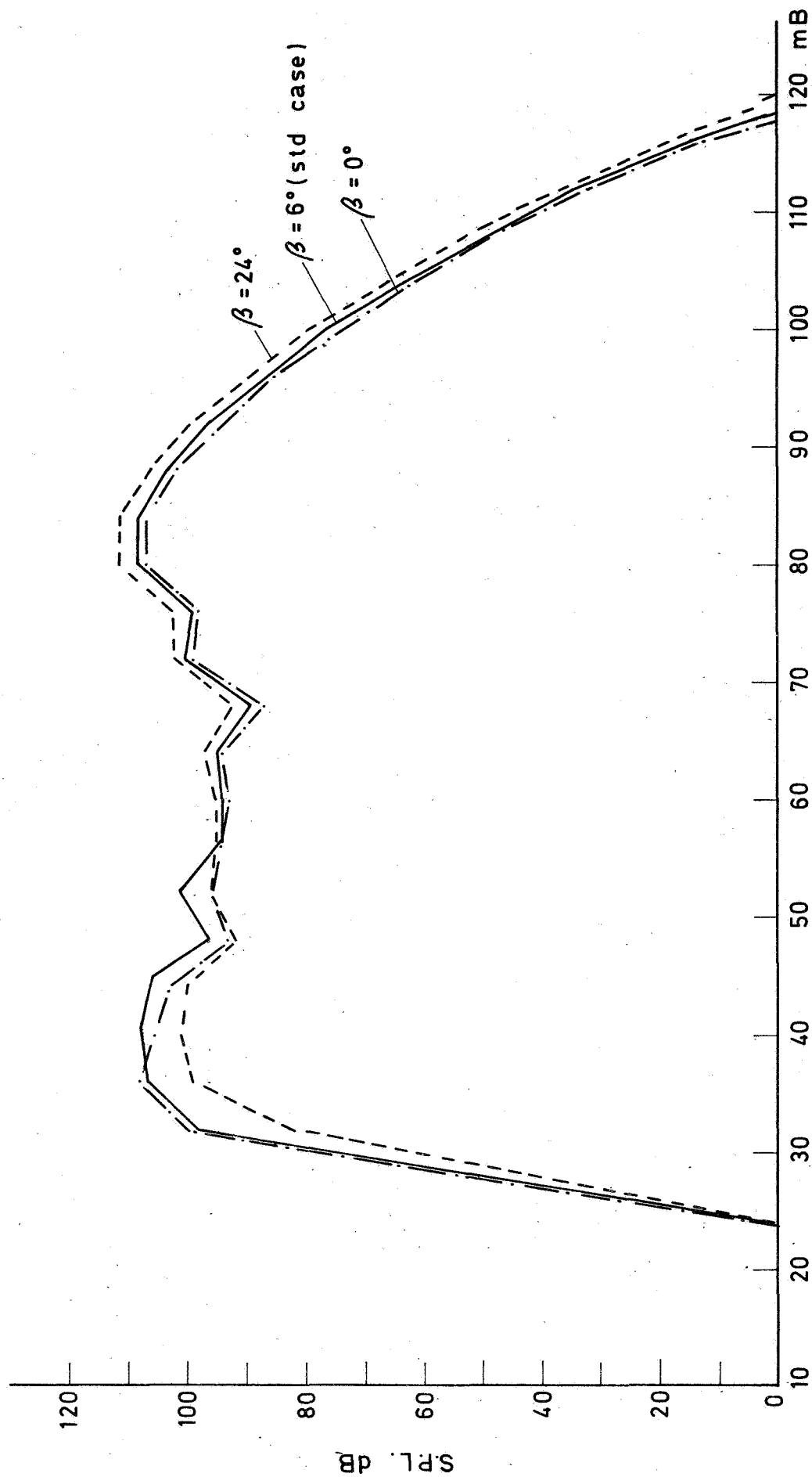
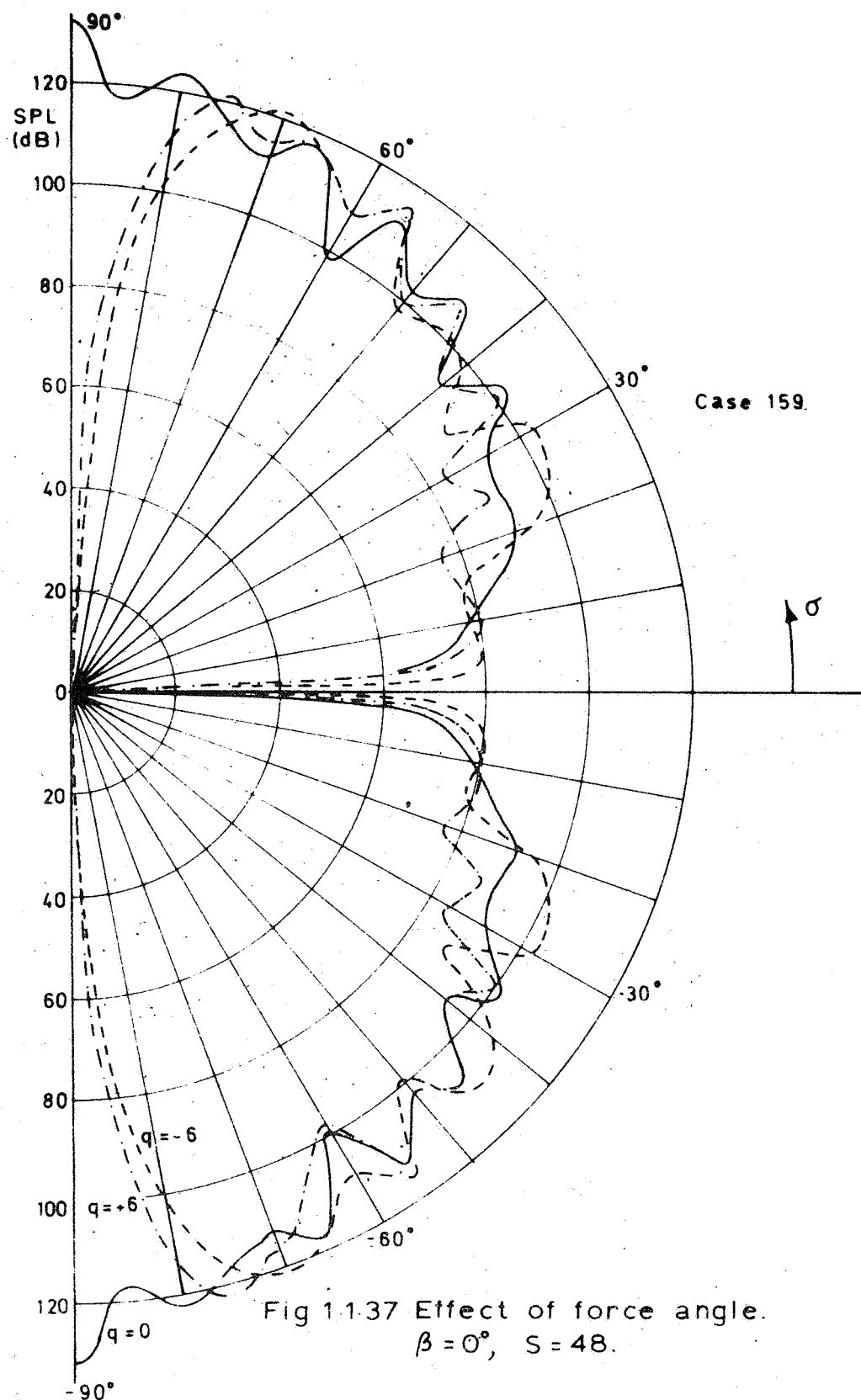


Fig.1-136 Effect of force angle  $S=48$ ,  $\sigma=-30^\circ$ .



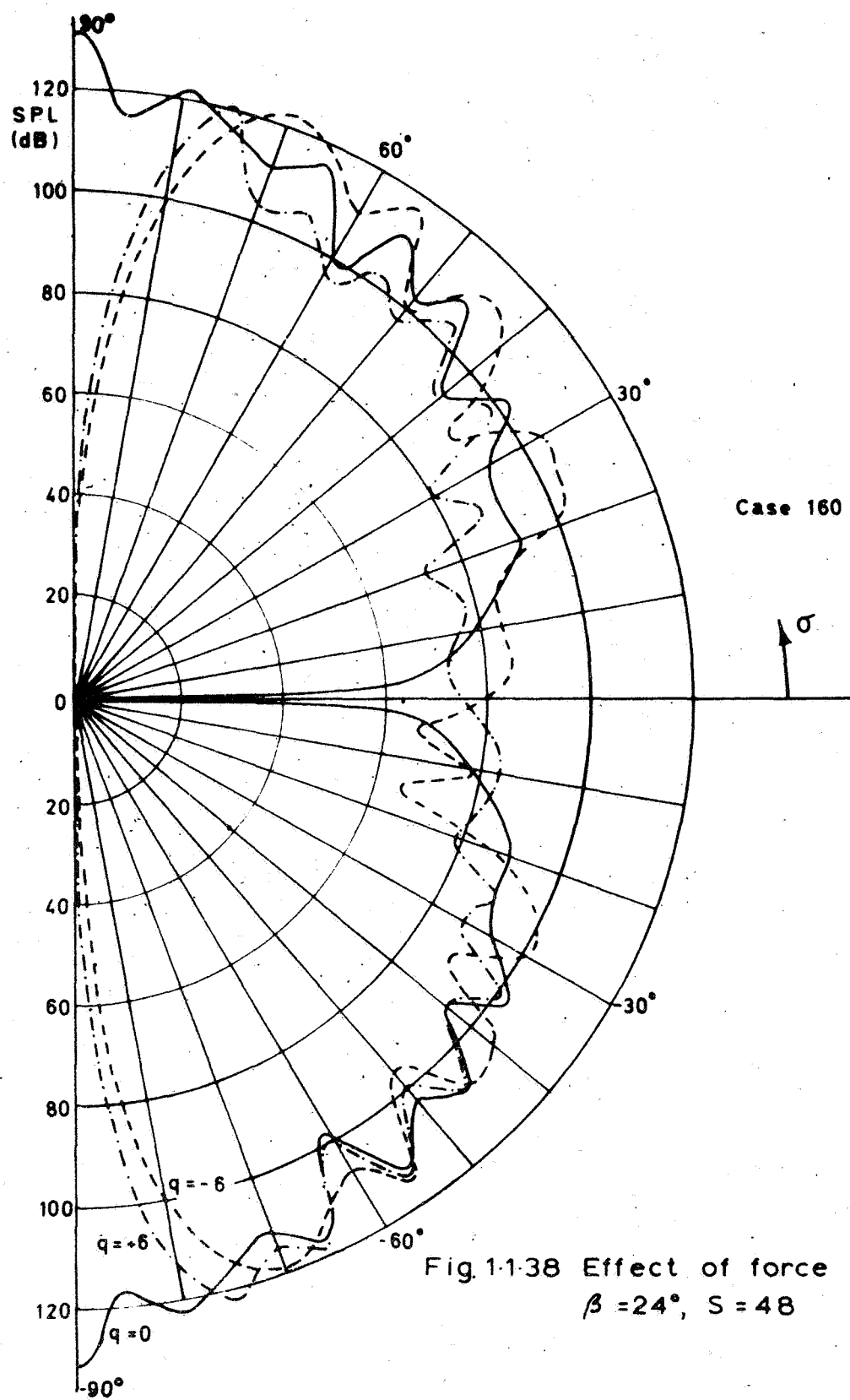


Fig. 1-1-38 Effect of force angle  
 $\beta = 24^\circ$ ,  $S = 48$

Case 141, 142, 143, 144.

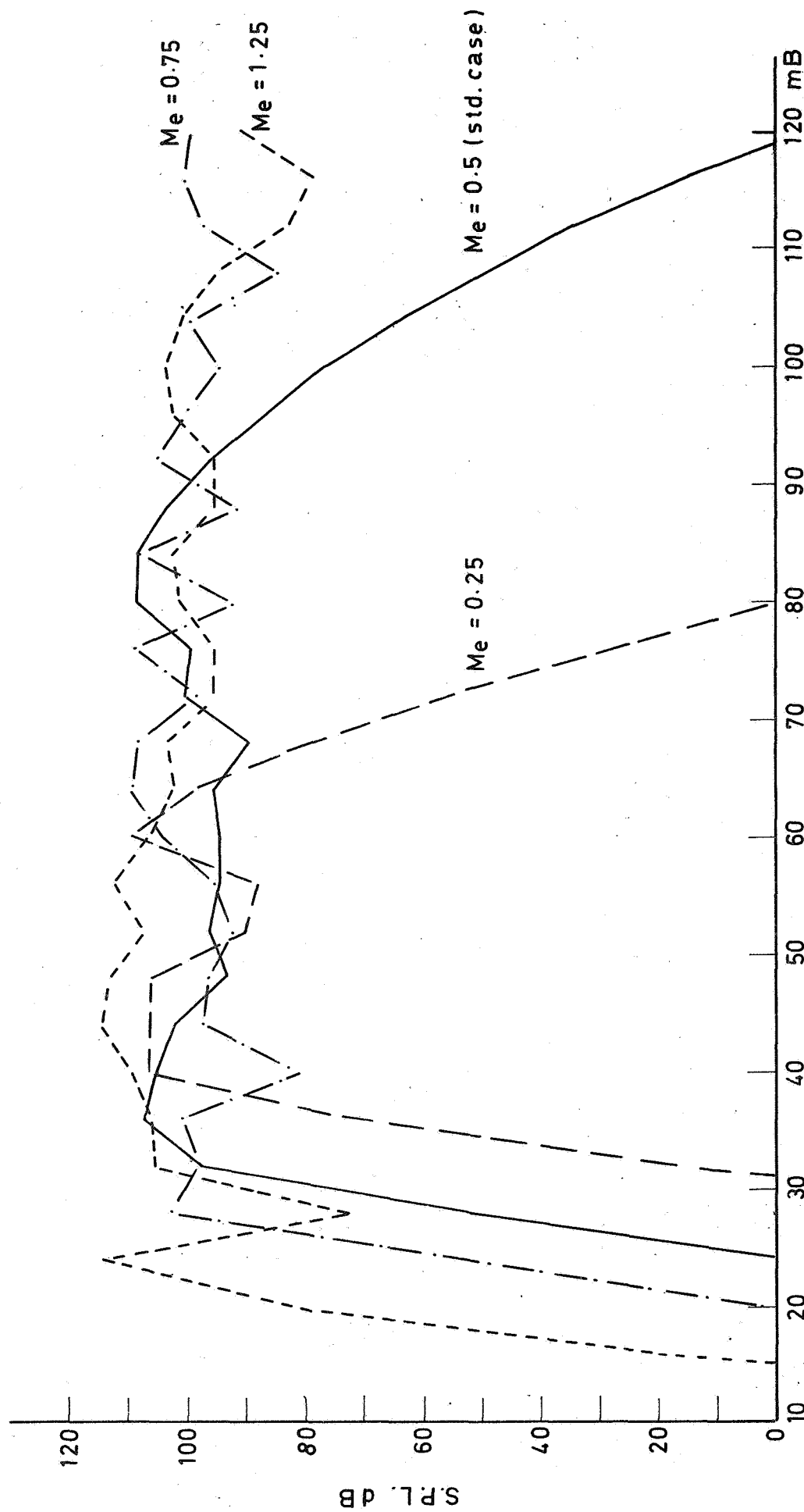


Fig. 1.1.39 Effect of Mach number  $S = 48$ ,  $\sigma = -30^\circ$

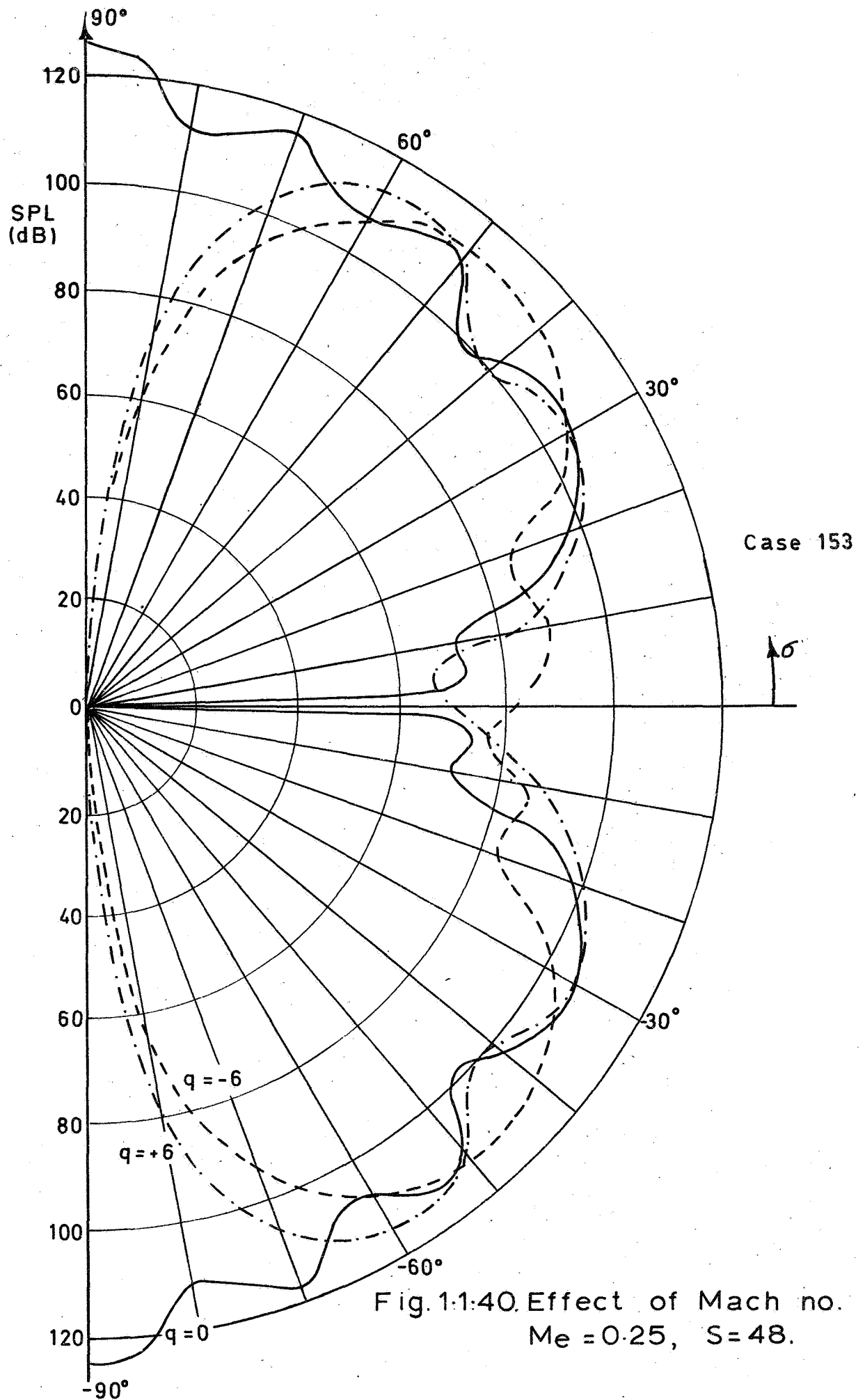
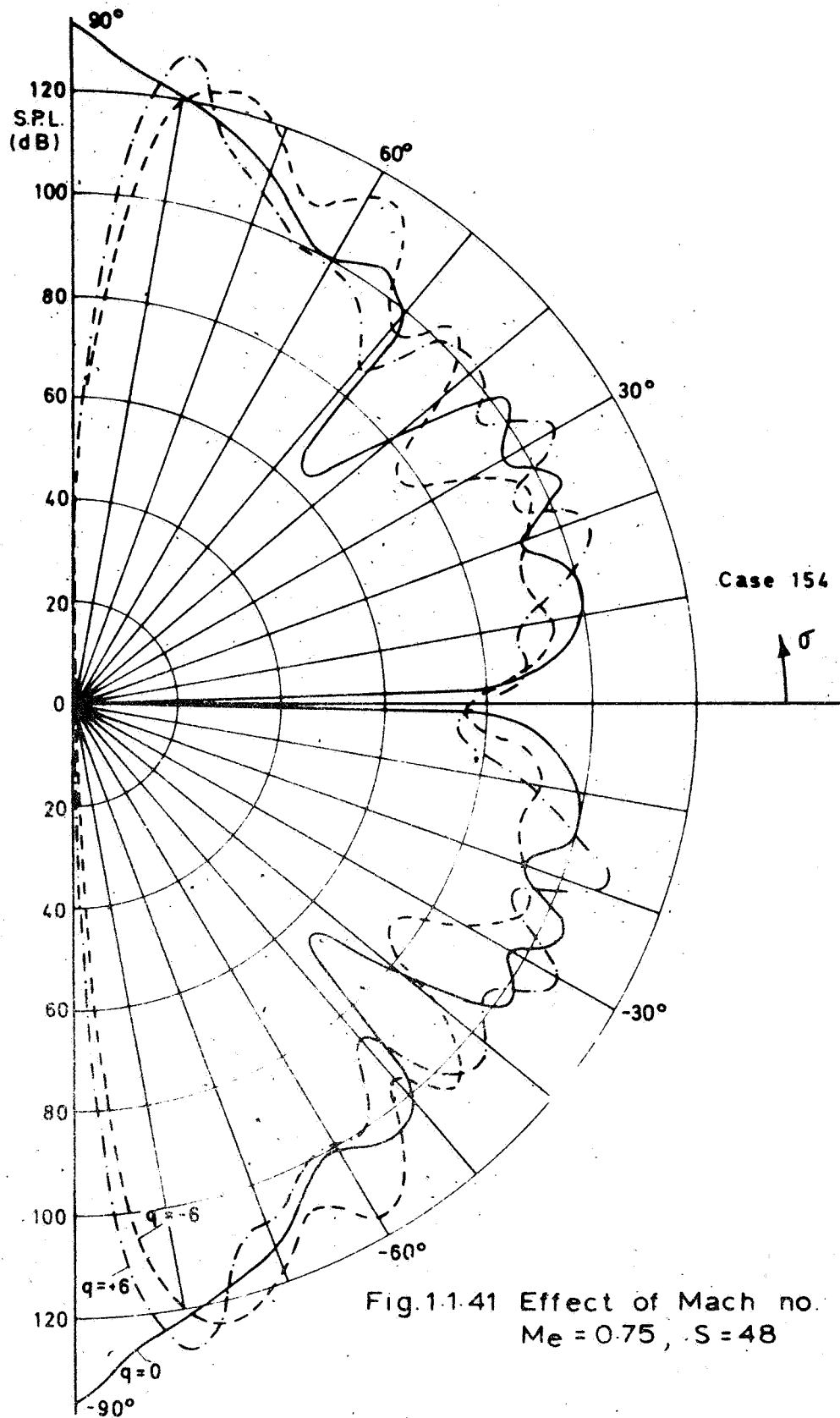
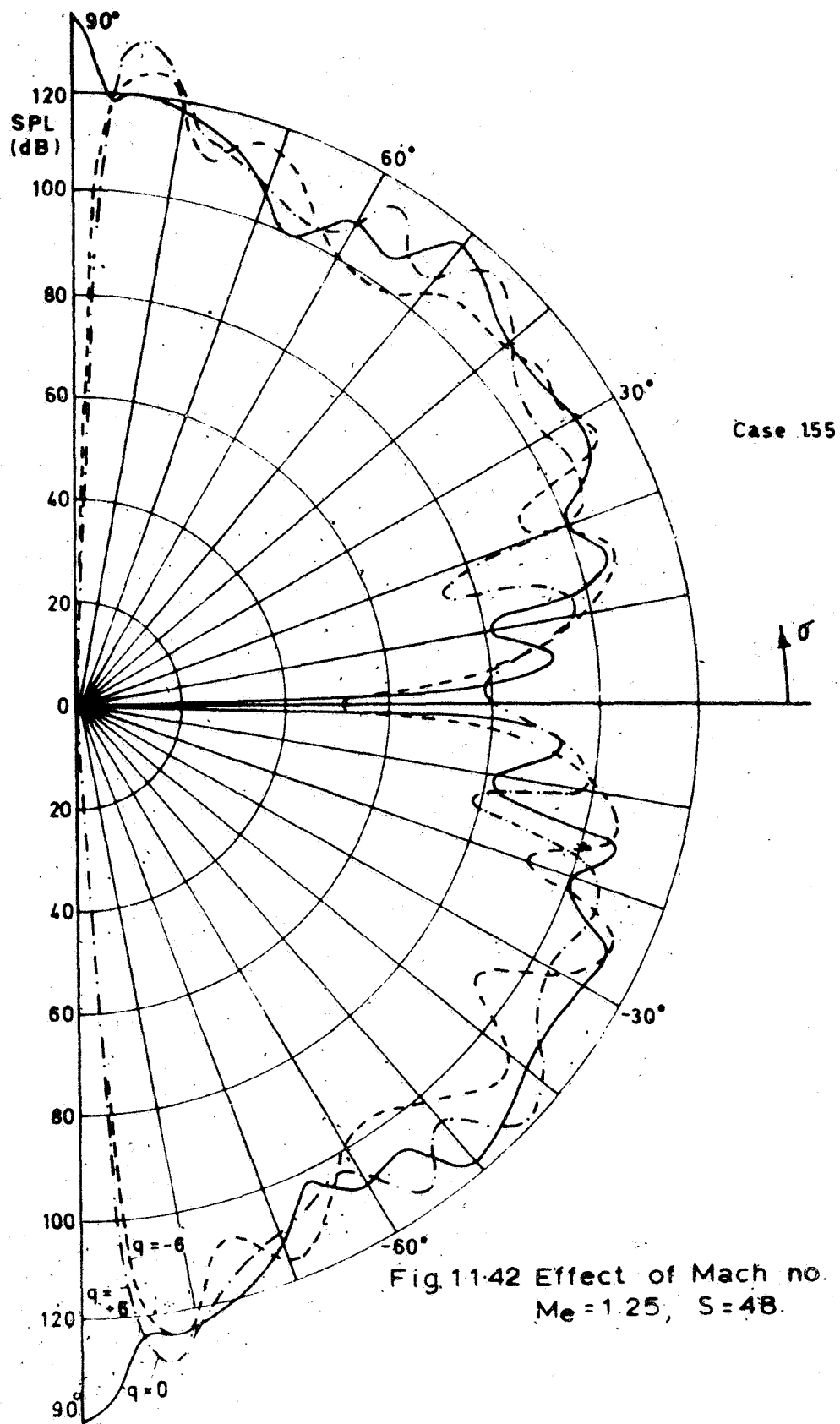
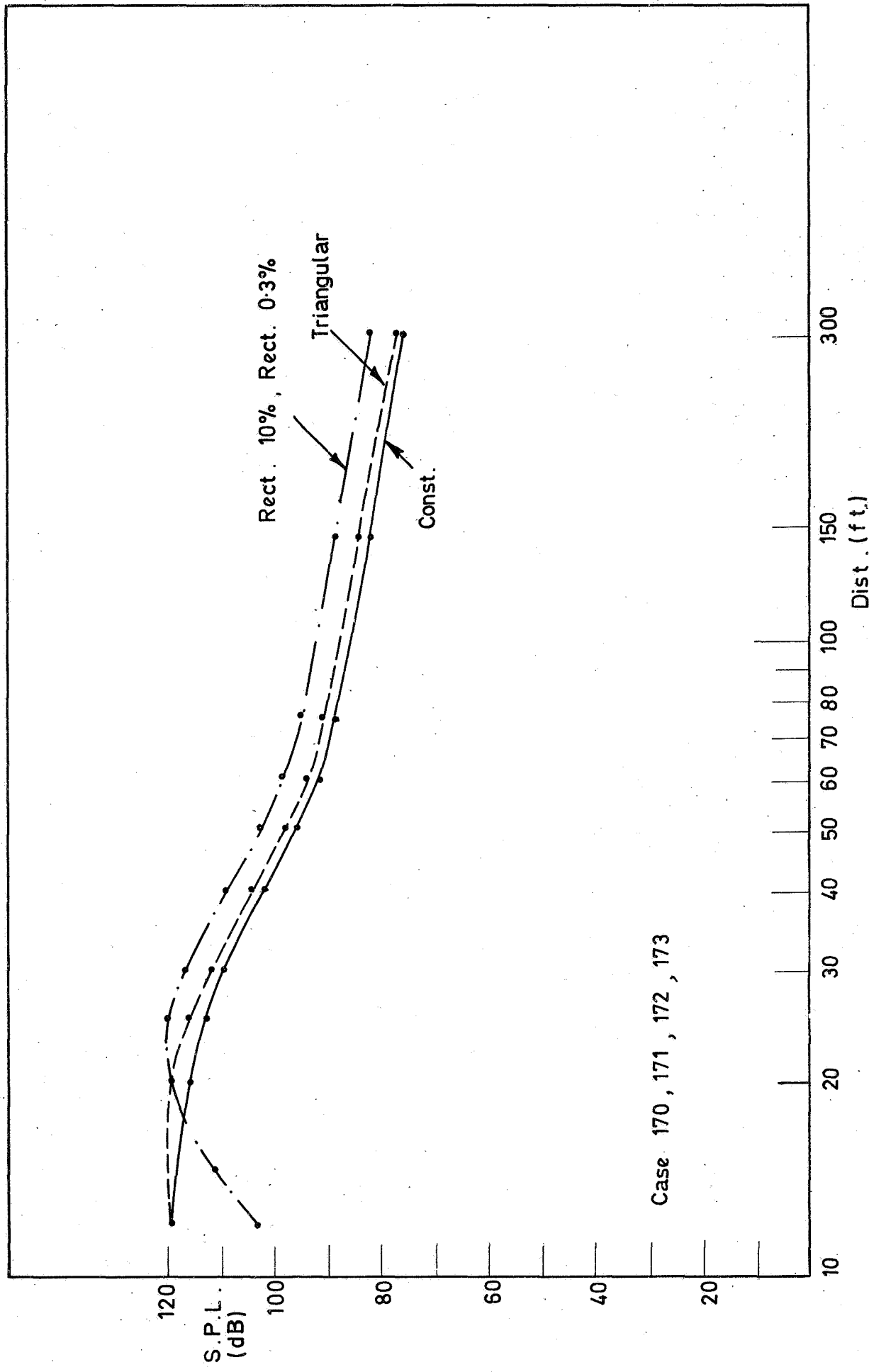


Fig. 1.1:40. Effect of Mach no.  
 $Me = 0.25$ ,  $S = 48$ .







Case 170, 171, 172, 173

Fig. 1-2-1. Near field - effect of span distribution  $S = 0$   $mB = 4$   
 $\sigma = -30^\circ$

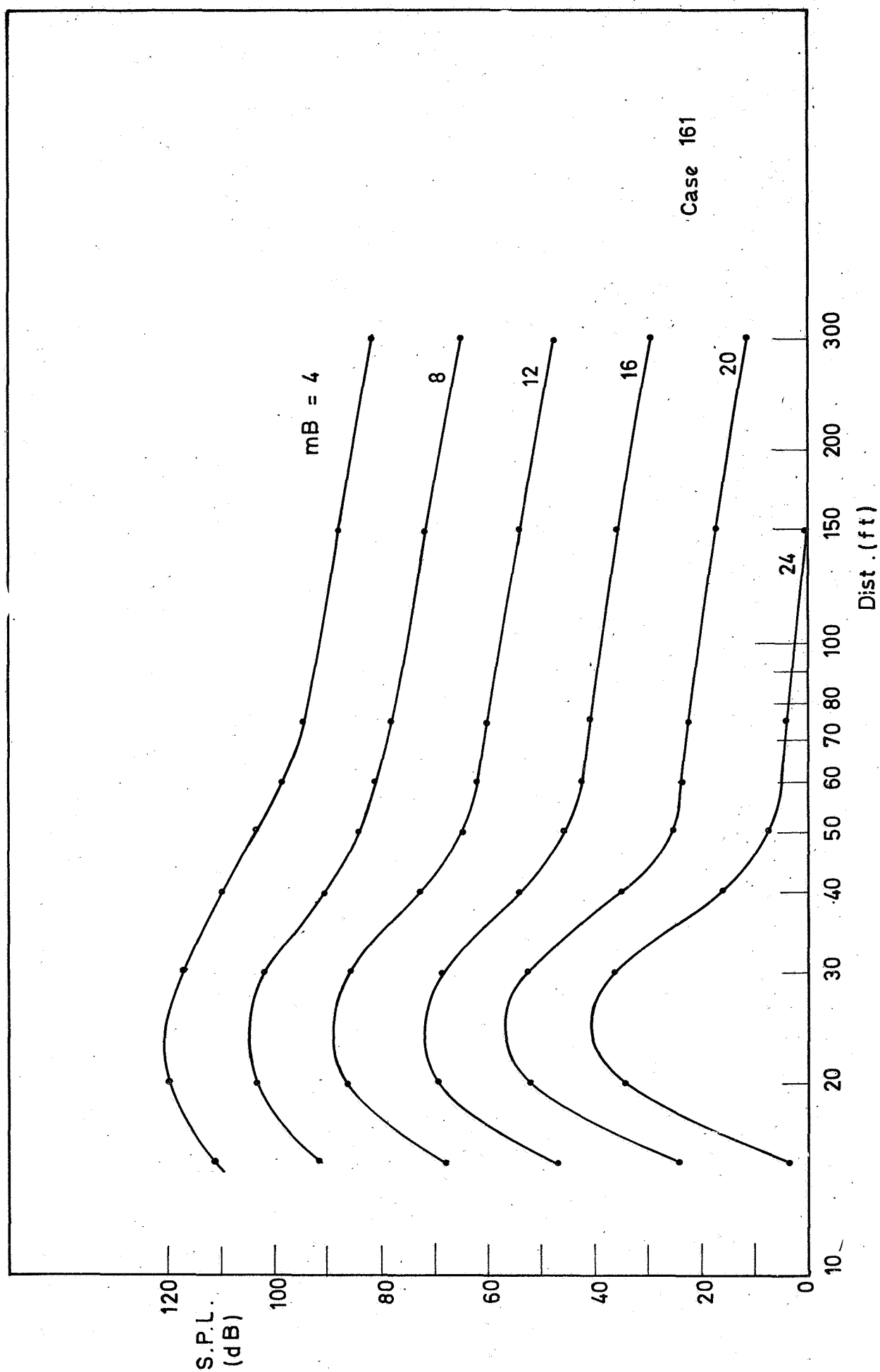


Fig. 1.2.2 Near field — effect of mB number.  $S = 0$   $\sigma = -30^\circ$

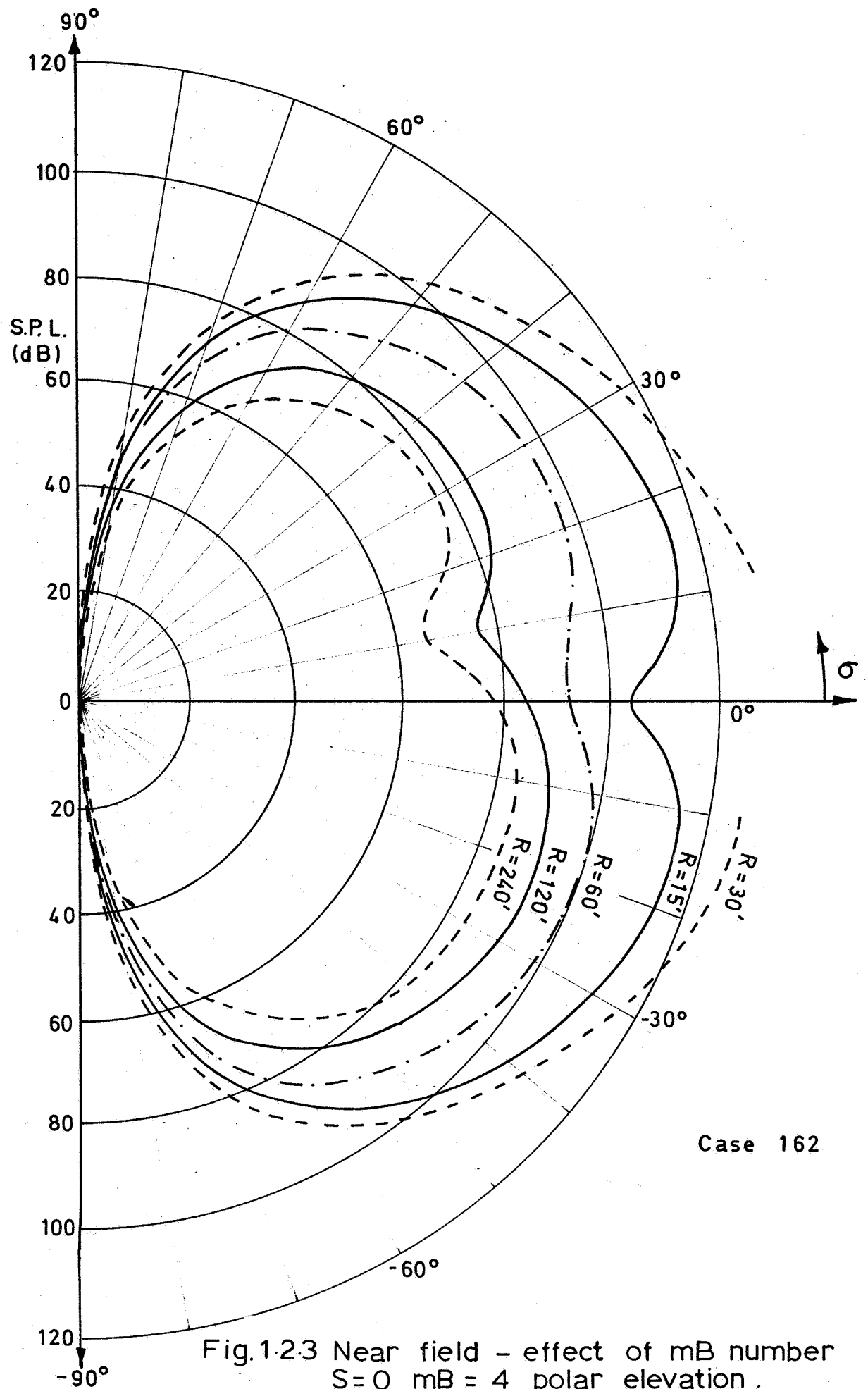


Fig.1.2.3 Near field - effect of mB number  
 $S=0$  mB = 4 polar elevation .

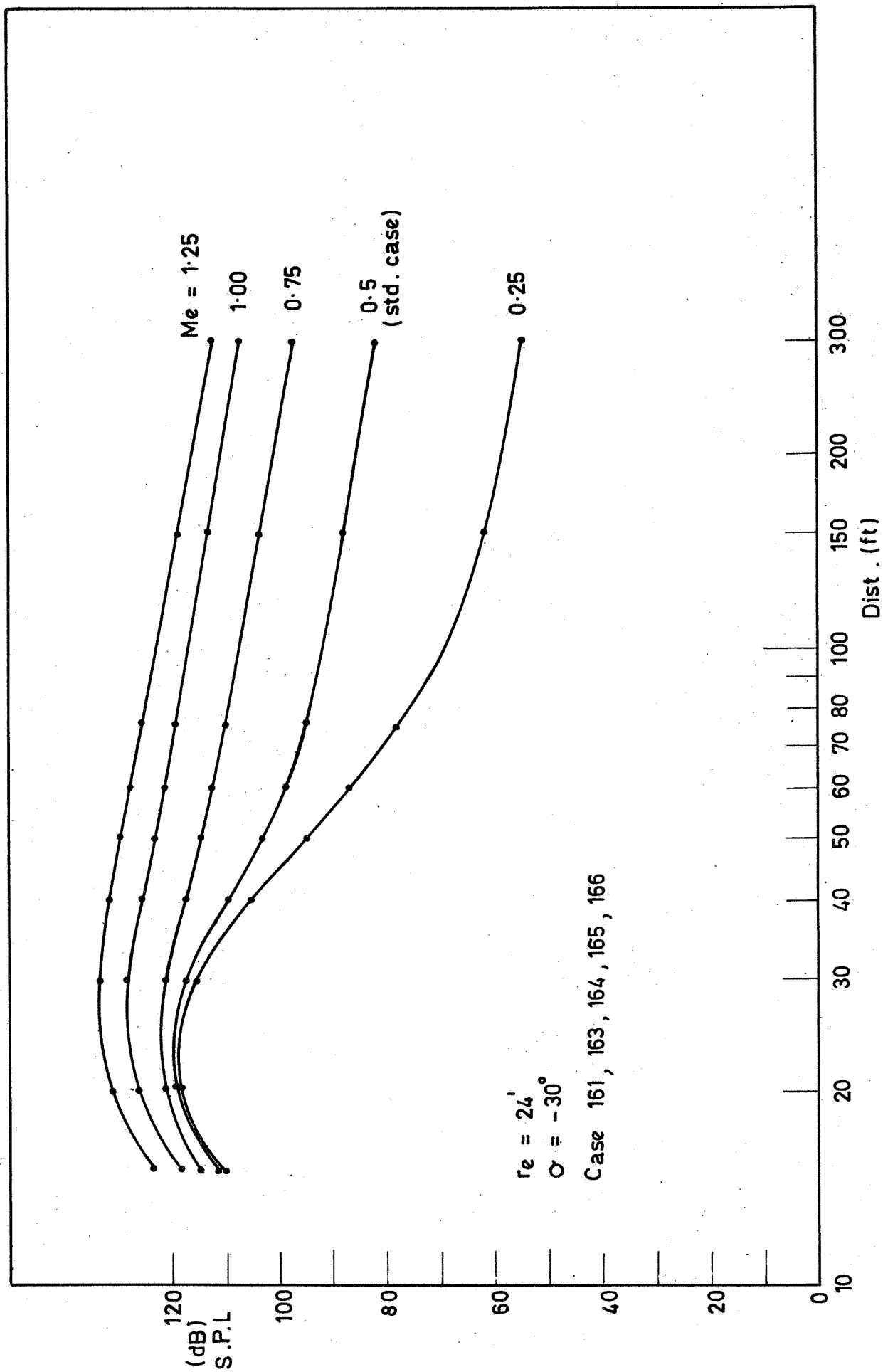


Fig. 1.2.4. Near field - effect of rotor speed.  $S = 0$   $mB = 4$

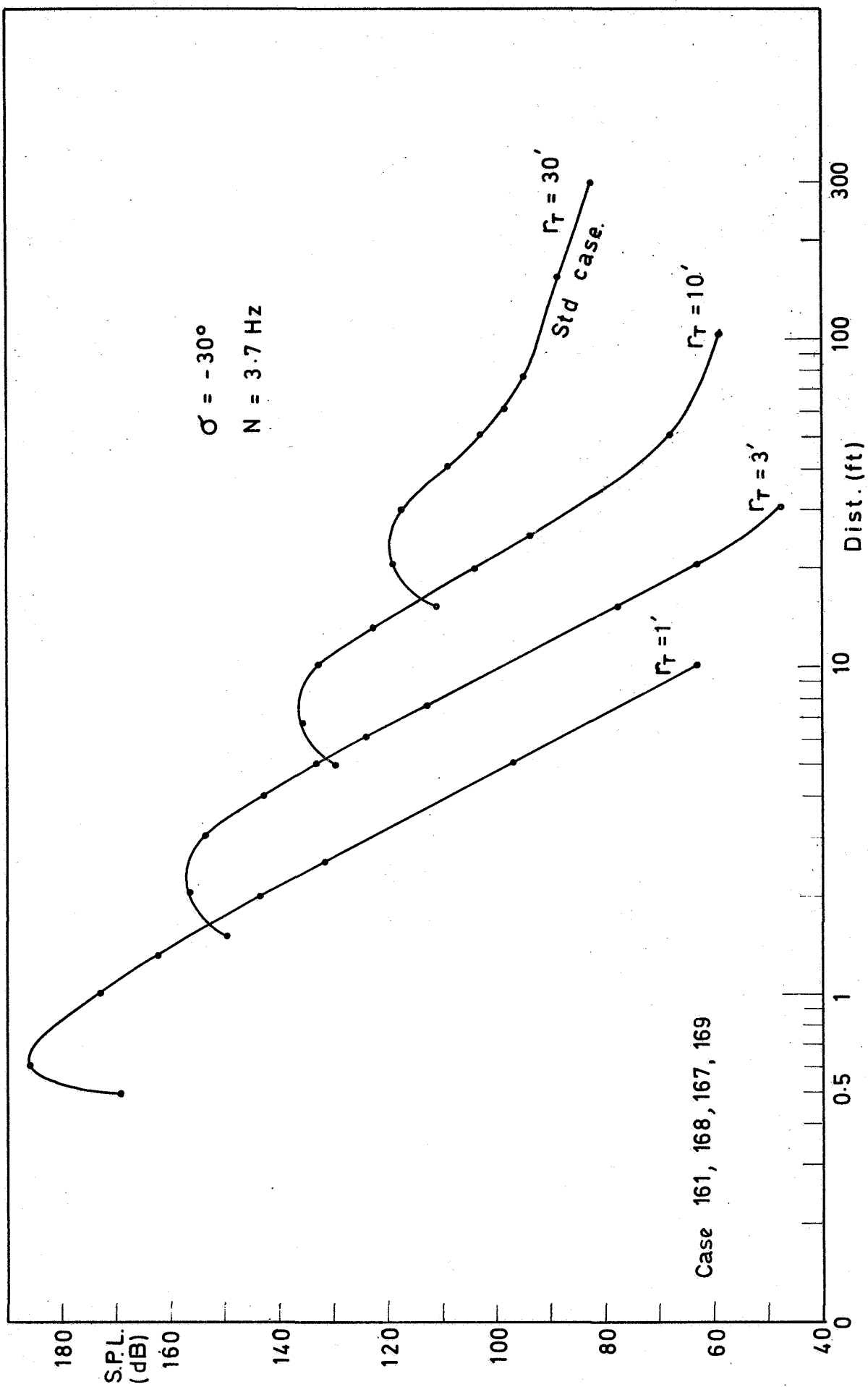


Fig. 1.2.5 Near field — effect of rotor radius  $s = 0$   $mB = 4$

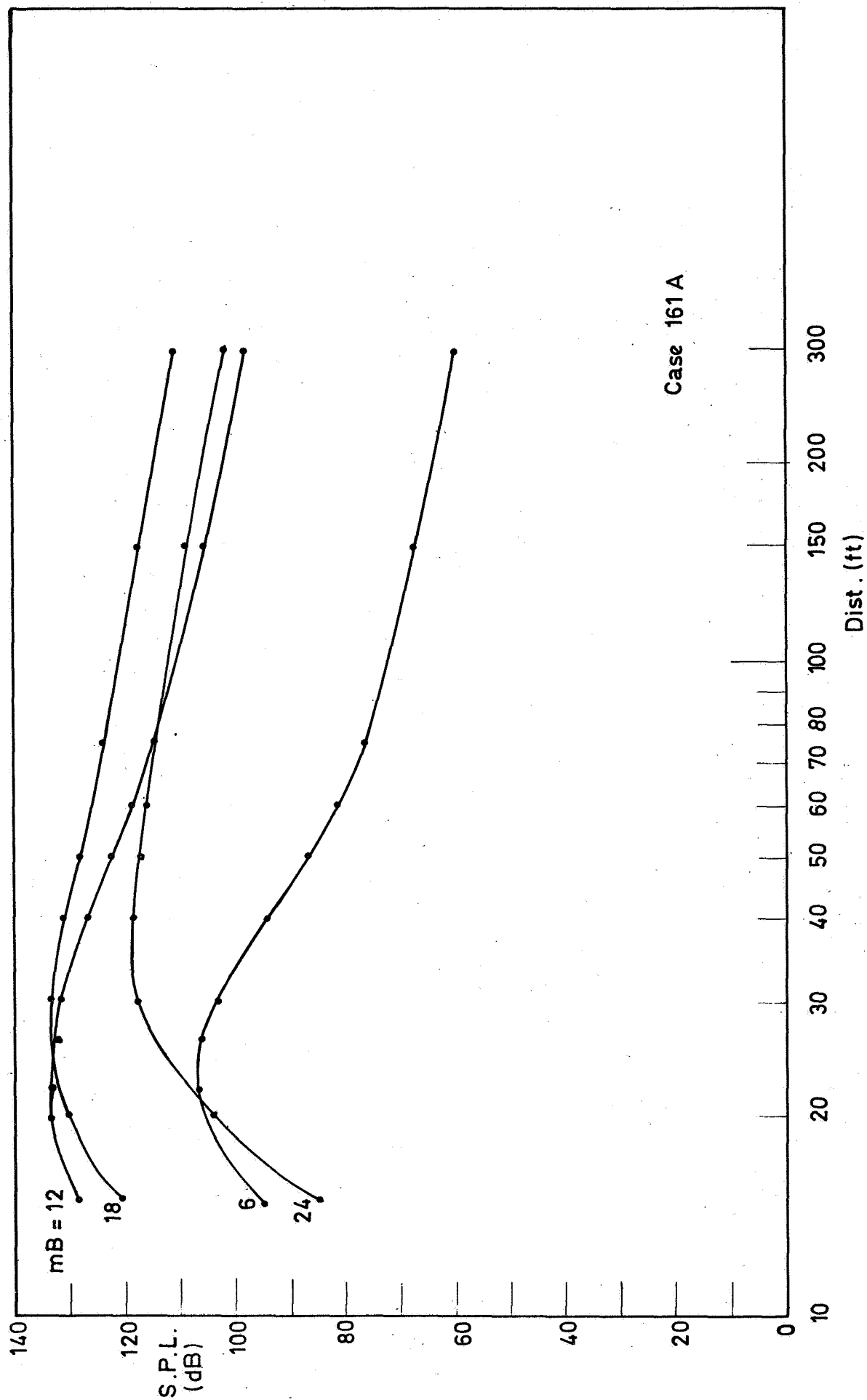


Fig. 1.2.6. Near field - effect of mB number.  $S = 12$   $\sigma = -30^\circ$

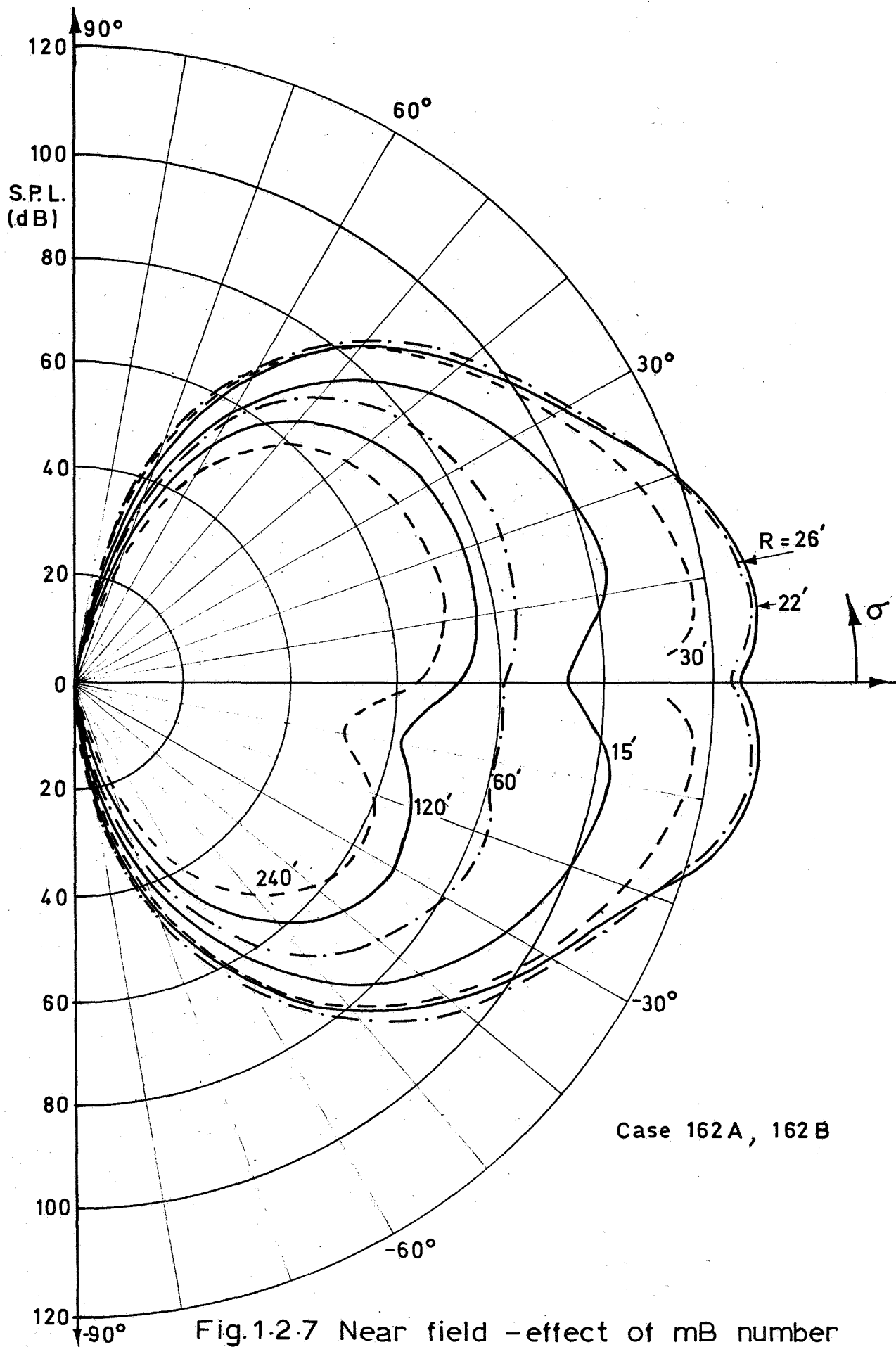
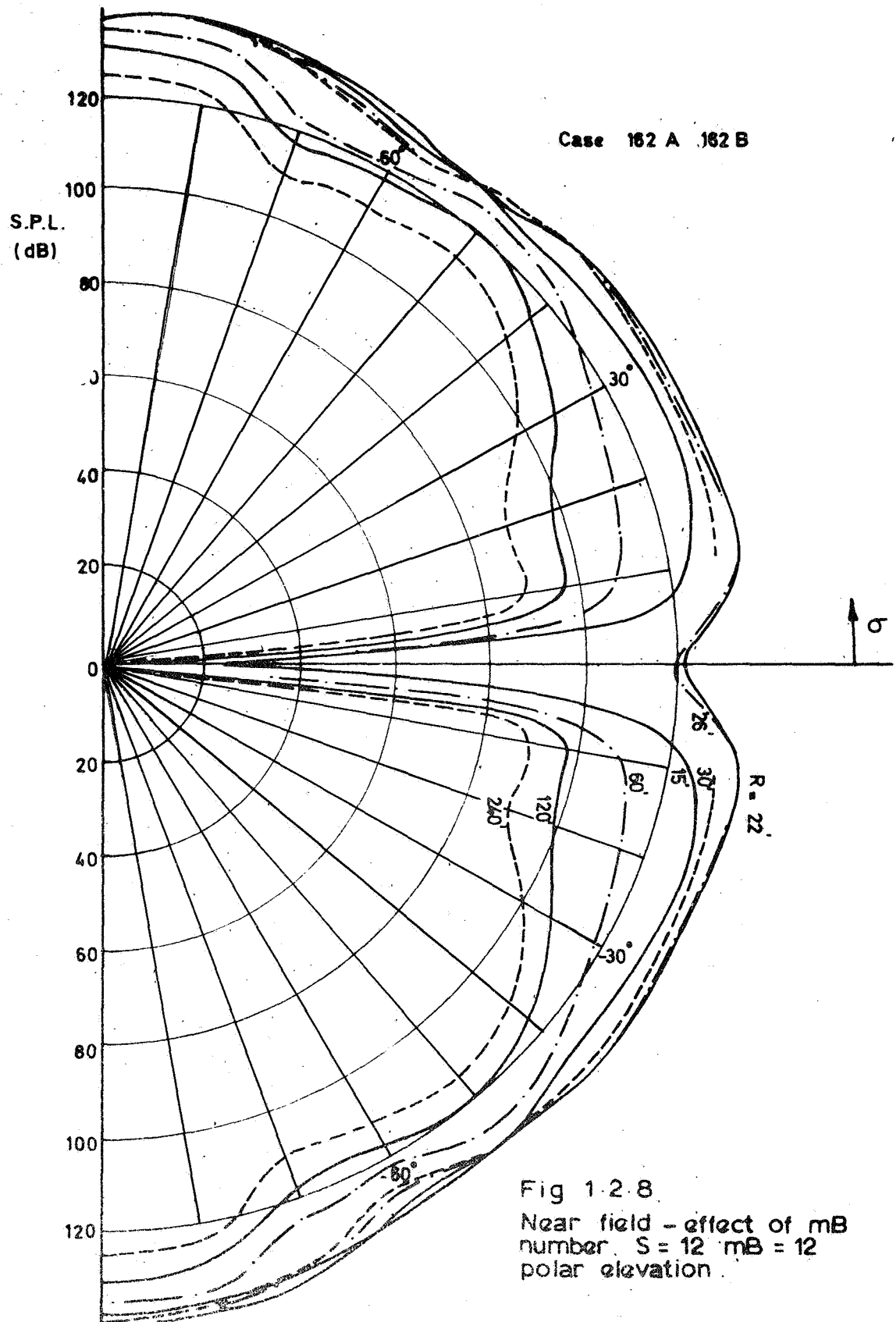
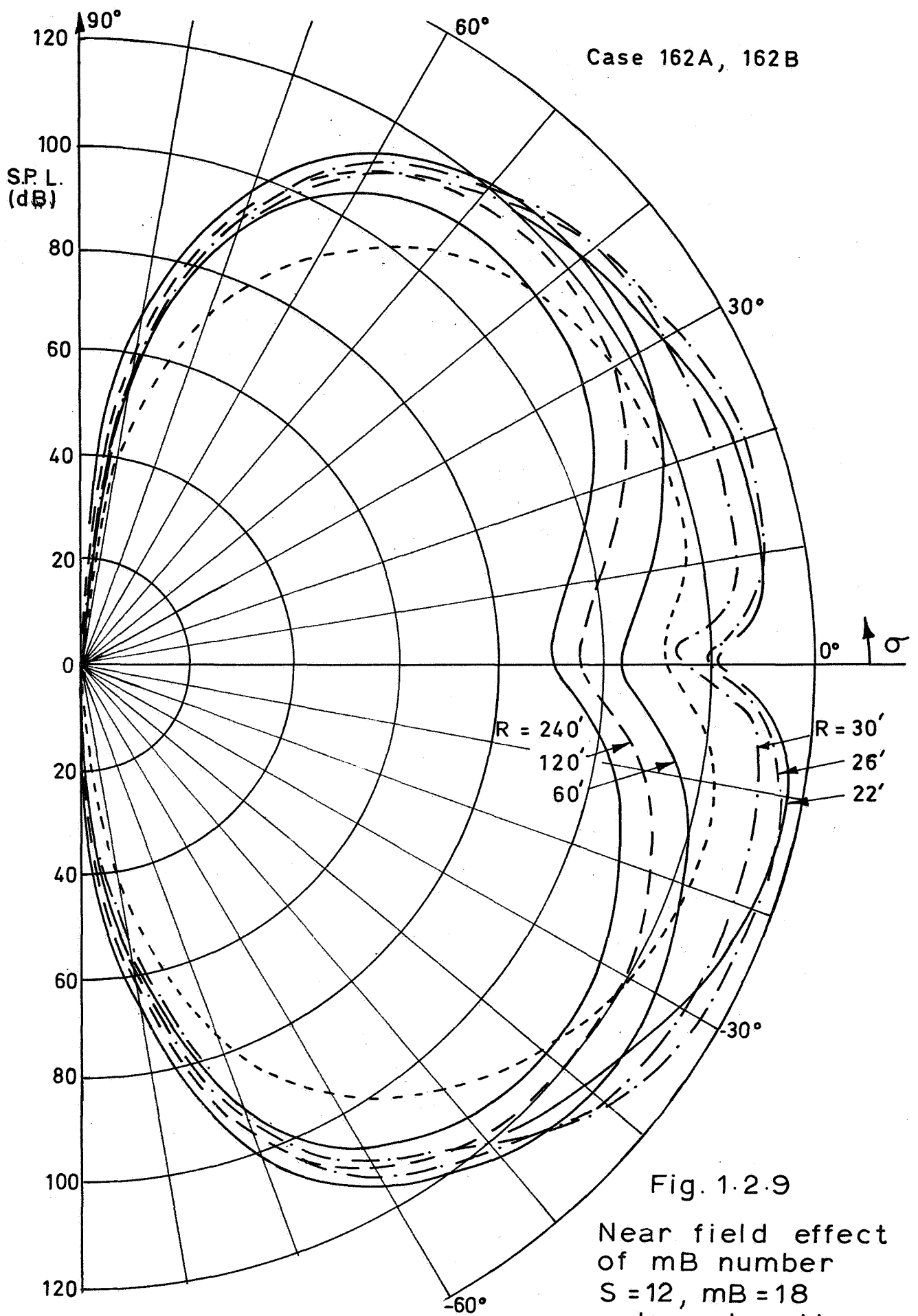


Fig.1-2.7 Near field -effect of mB number  
 S = 12 mB = 6 polar elevation.





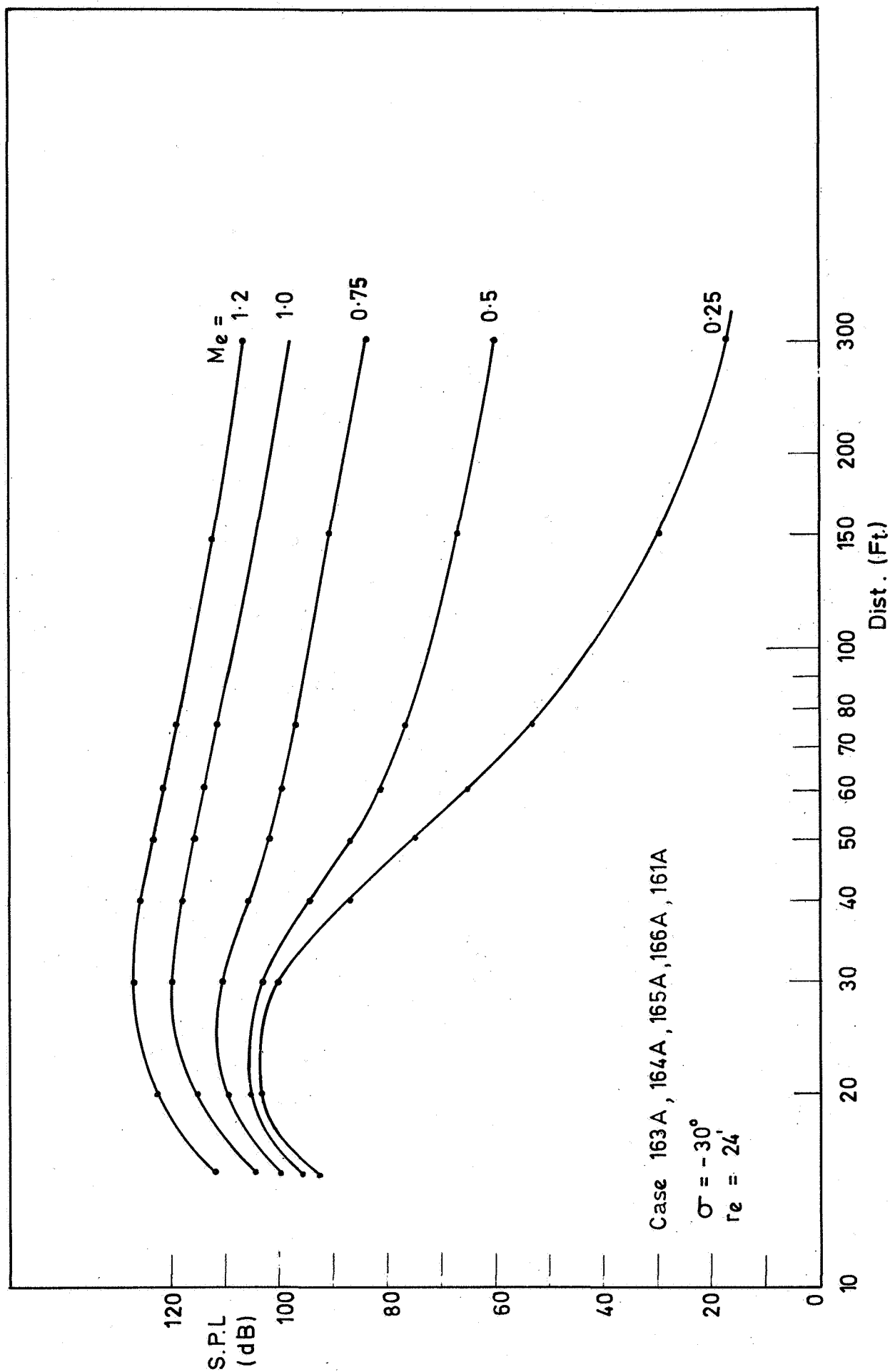


Fig. 1.2.10 Near field - effect of rotor speed  $S = 12$   $mB = 6$

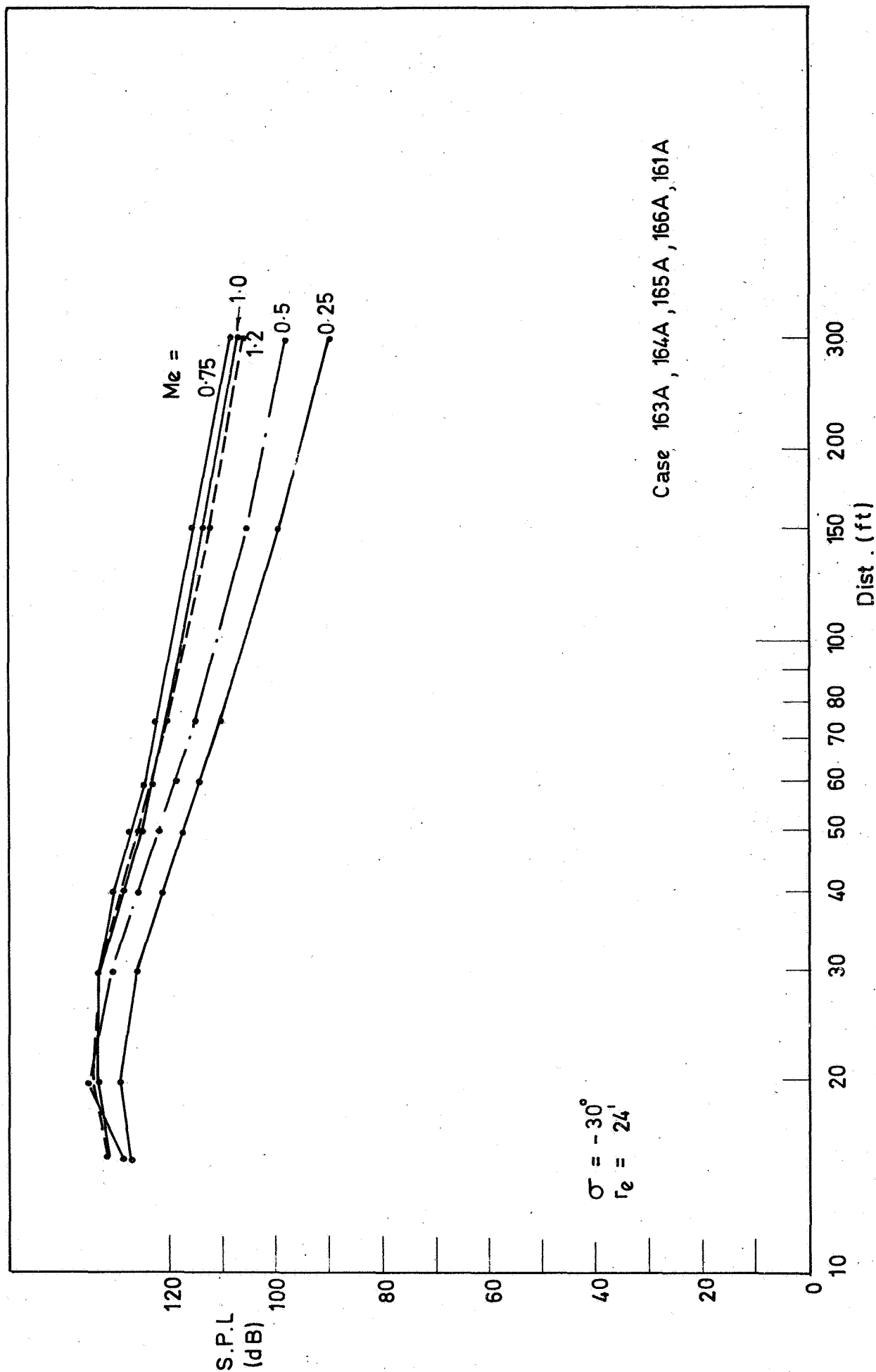


Fig. 1.2.11 Near field — effect of rotor speed.  $S = 12$   $mB = 12$

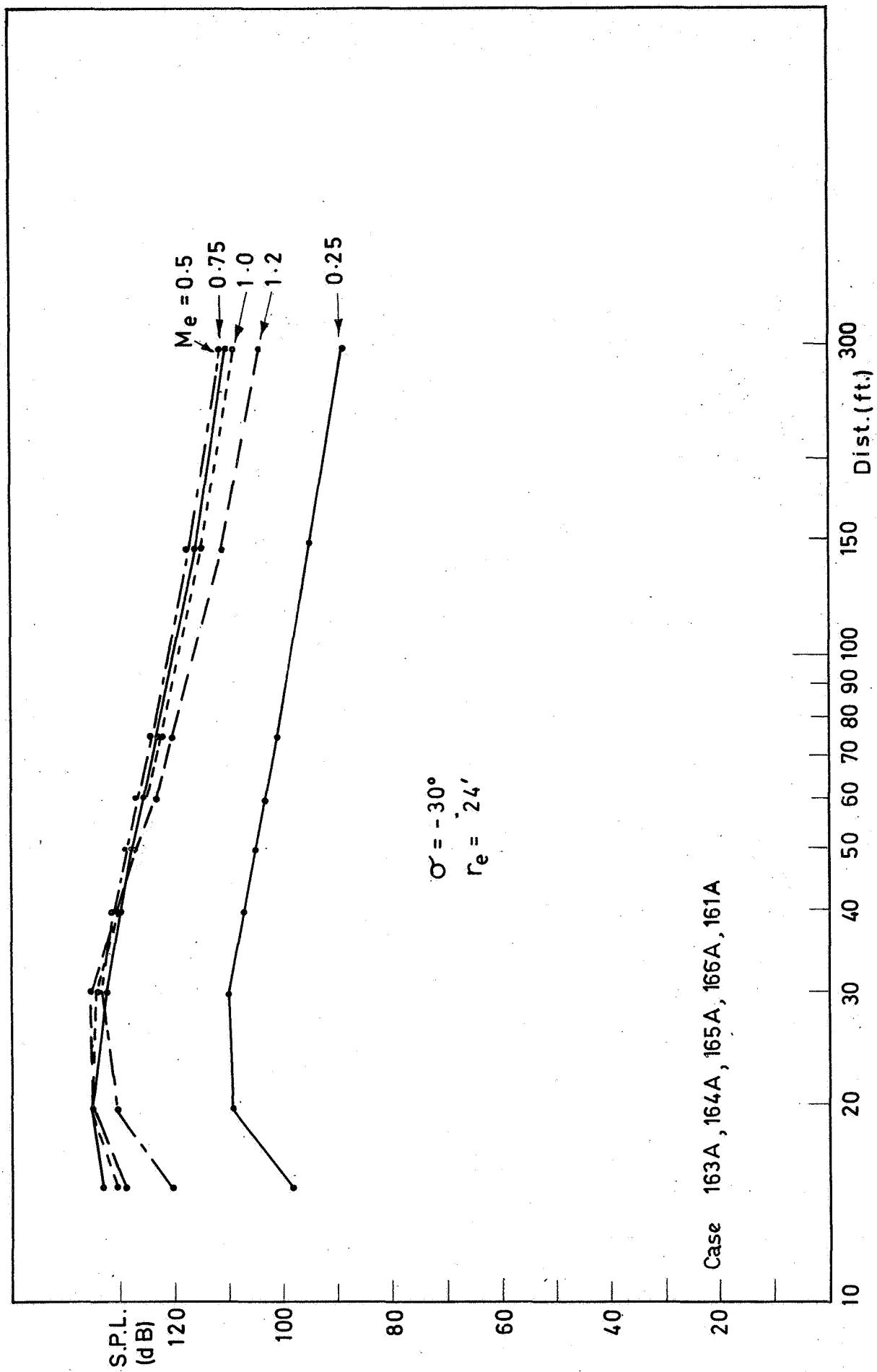


Fig. 1-2-12 Near field — effect of rotor speed  $s=12$ ,  $mB=18$

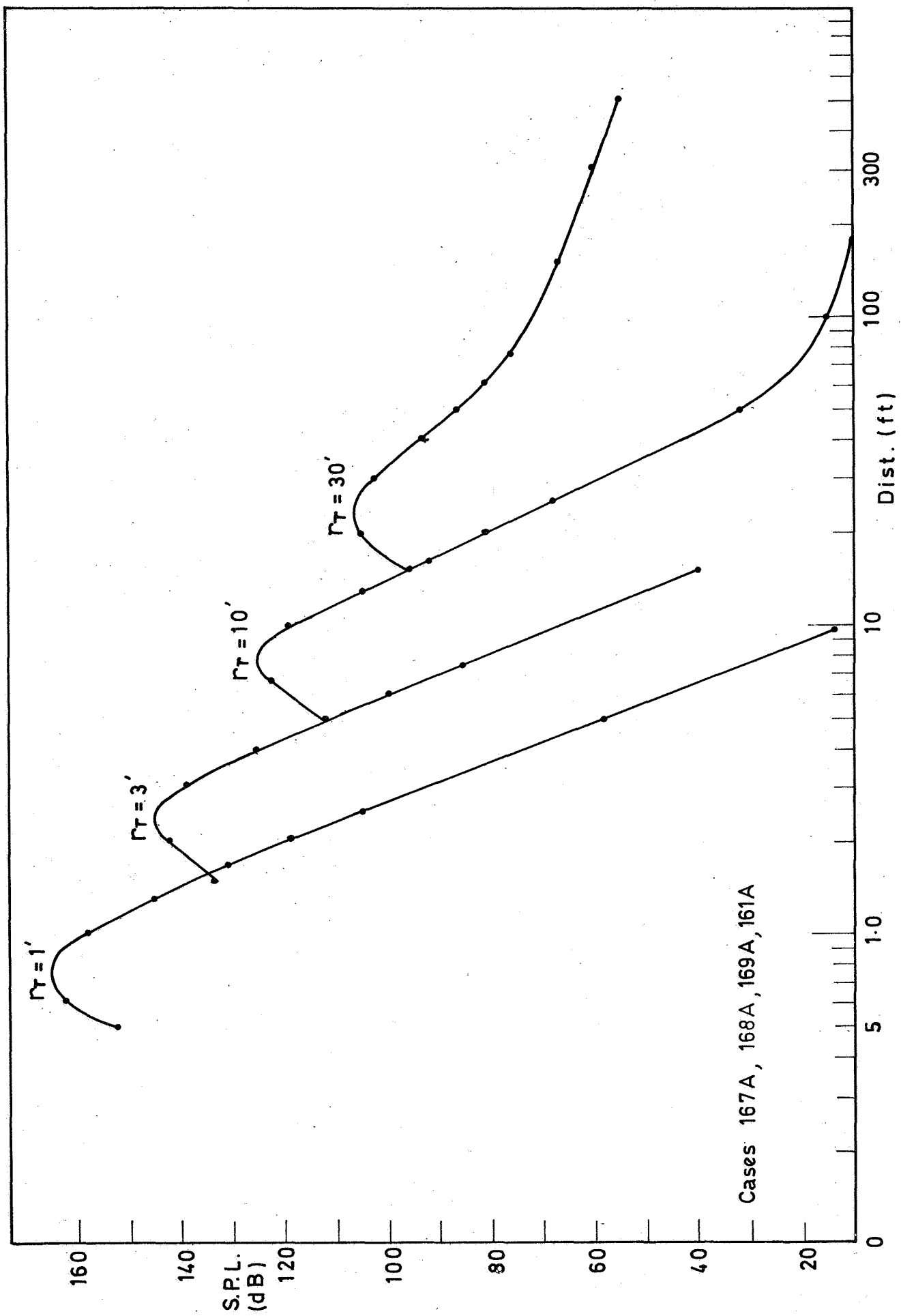


Fig. 1.2.13 Near field — effect of rotor radius  $s = 12$   $mB = 6$

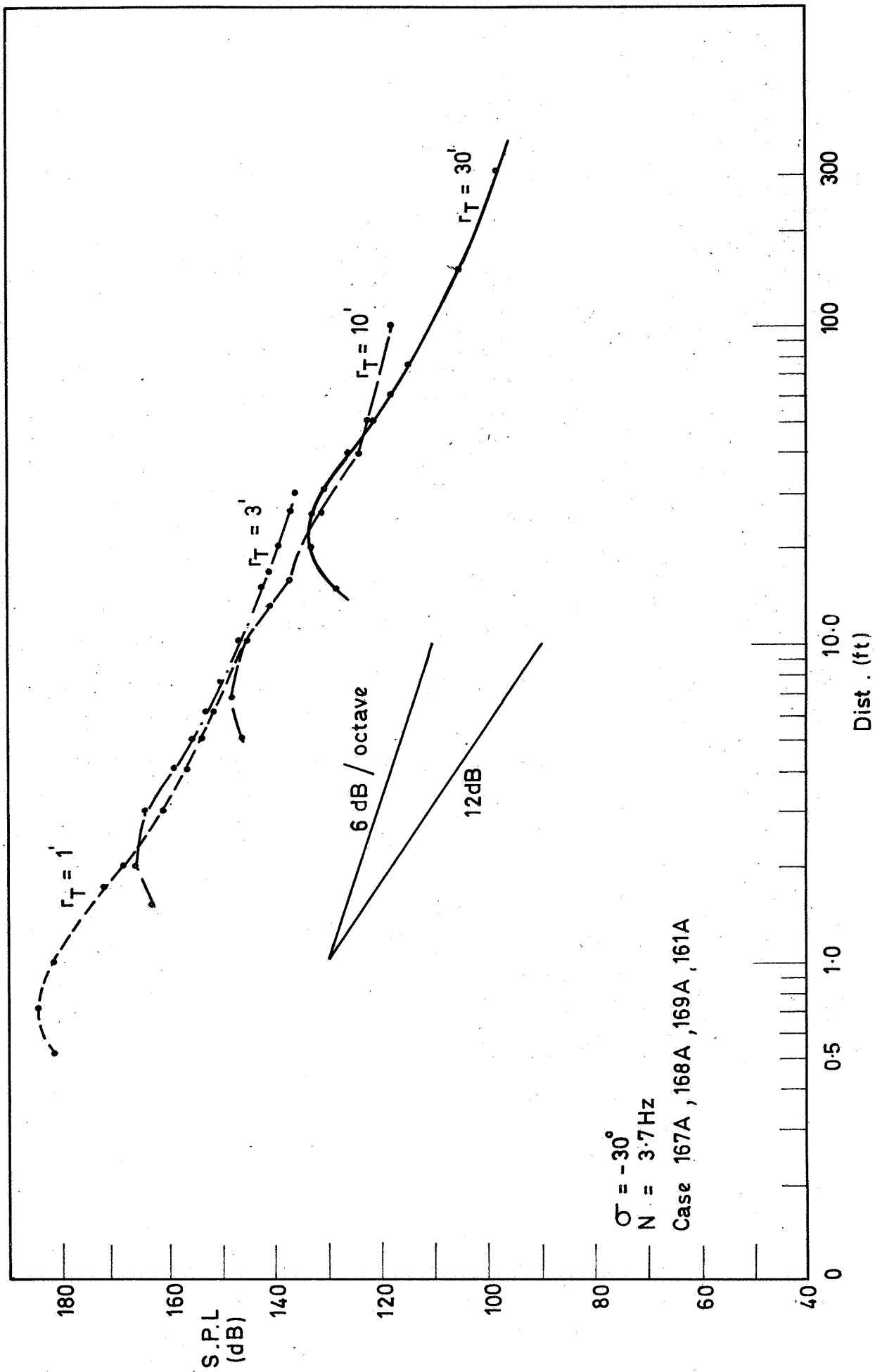


Fig. 1.2.14 Near field — effect of rotor radius.  $S = 12$   $\text{mB} = 12$

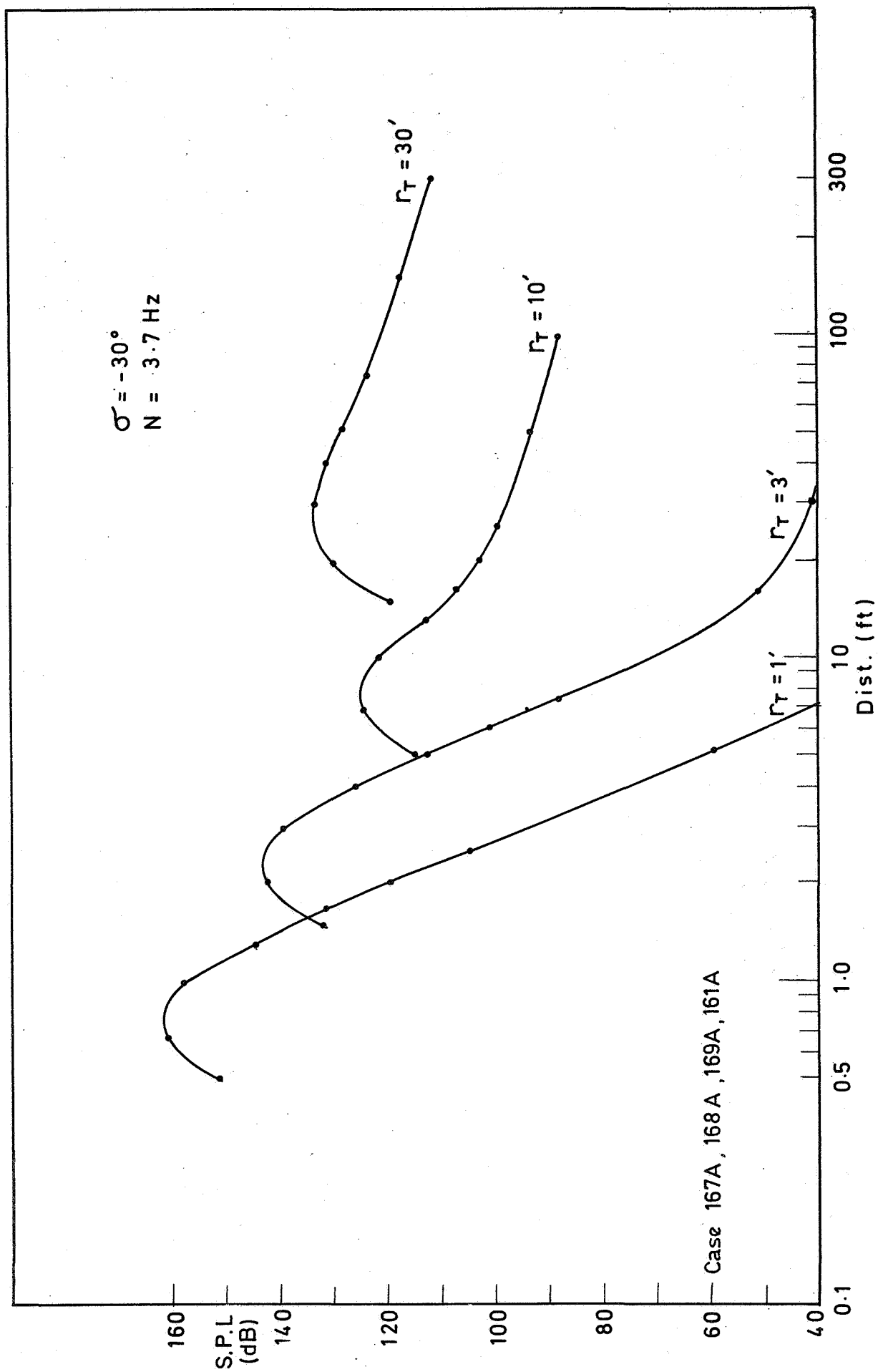


Fig. 1.2.15 Near field — effect of rotor radius  $S=12$   $mB=18$

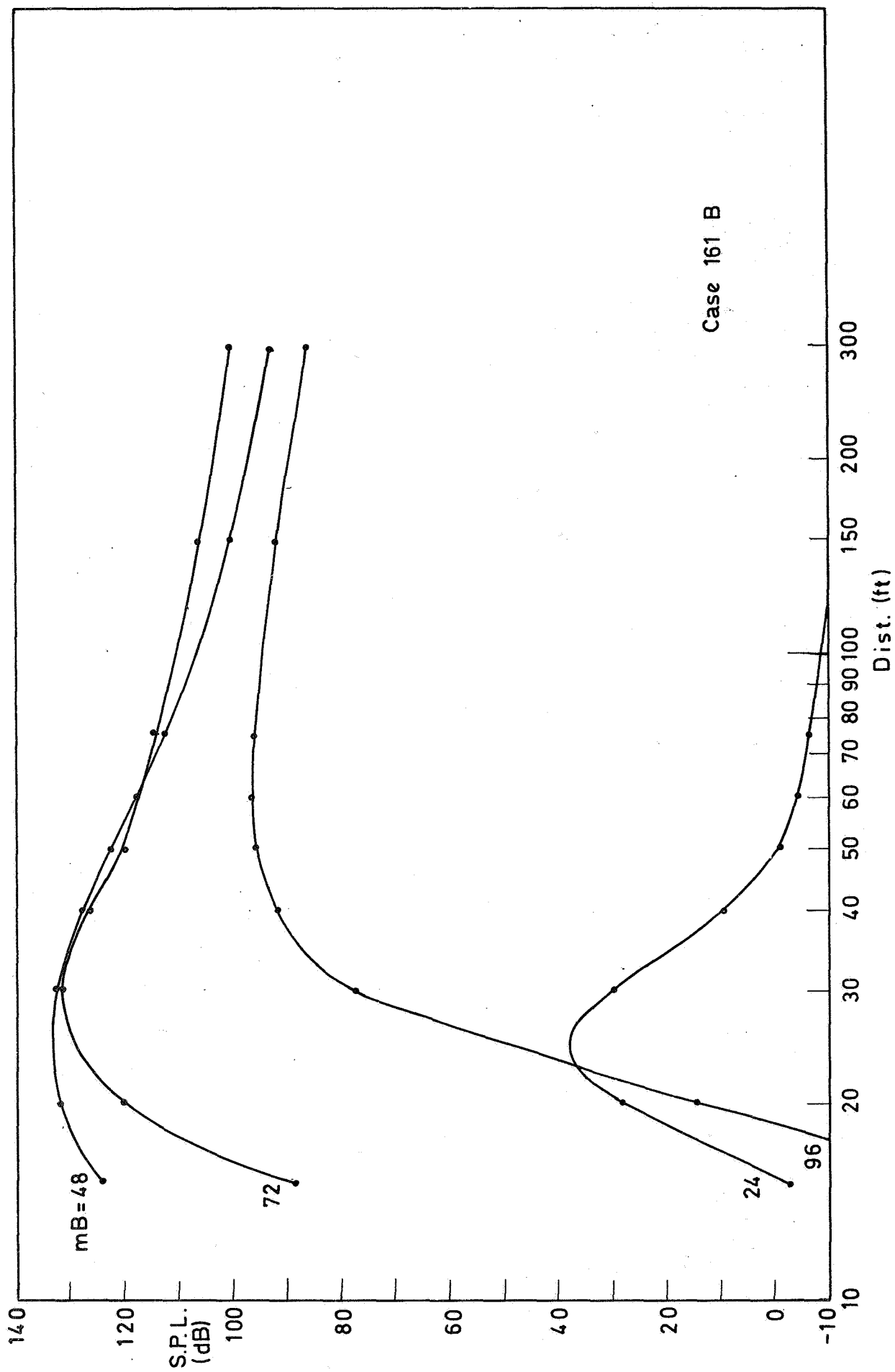


Fig. 1.2.16 Near field - effect of mB number.  $S = 48$   $\sigma = -30$

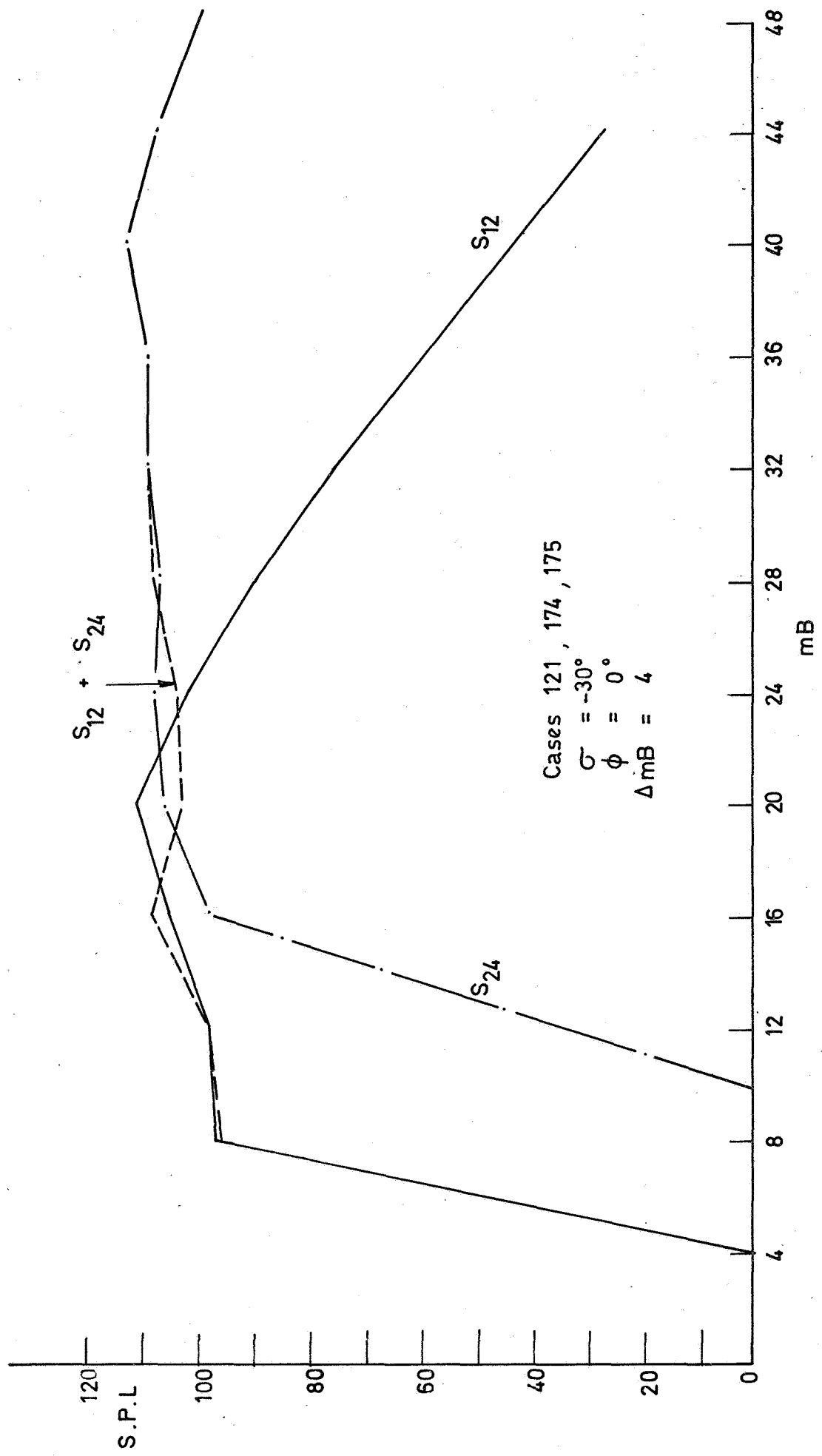


Fig.2.11 Simple B.L.H radiation addition  $S_{12} + S_{24}$

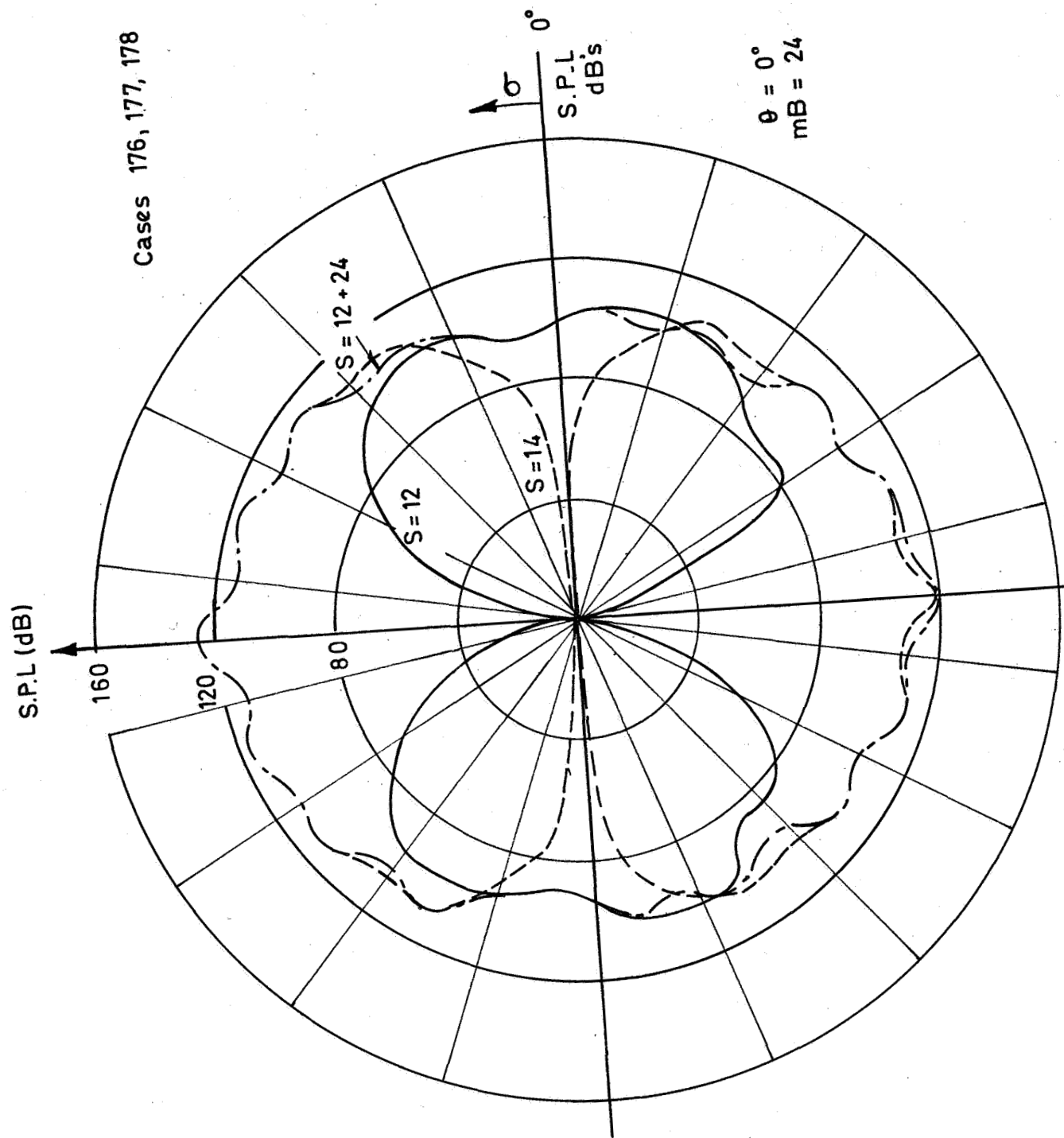


Fig. 2.1.2 Simple B.L.H. addition  $S_{12} + S_{24}$  polar elevation

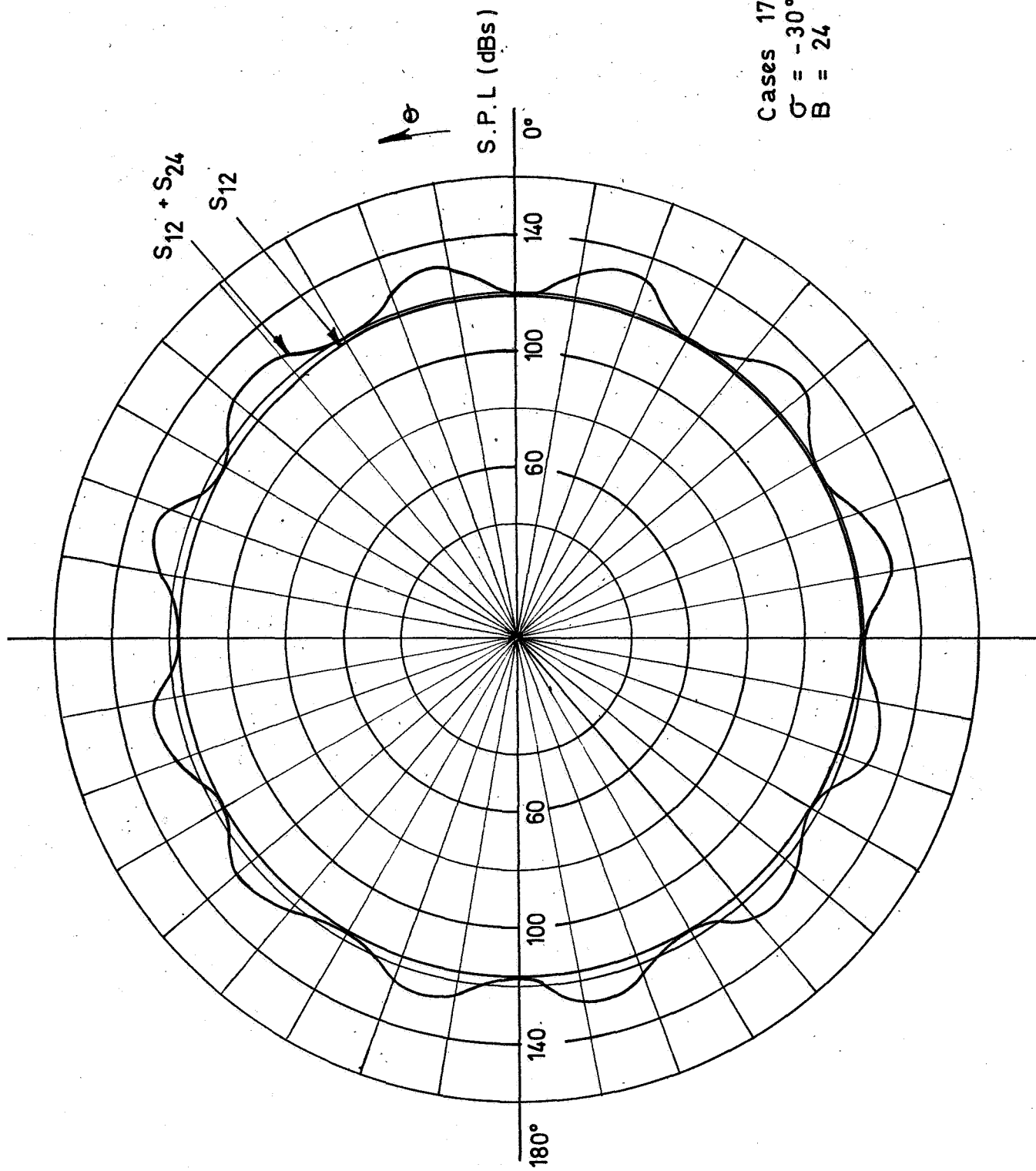


Fig. 2.1.3 Simple B.L.H radiation addition  $S_{12} + S_{24}$  · Polar plan

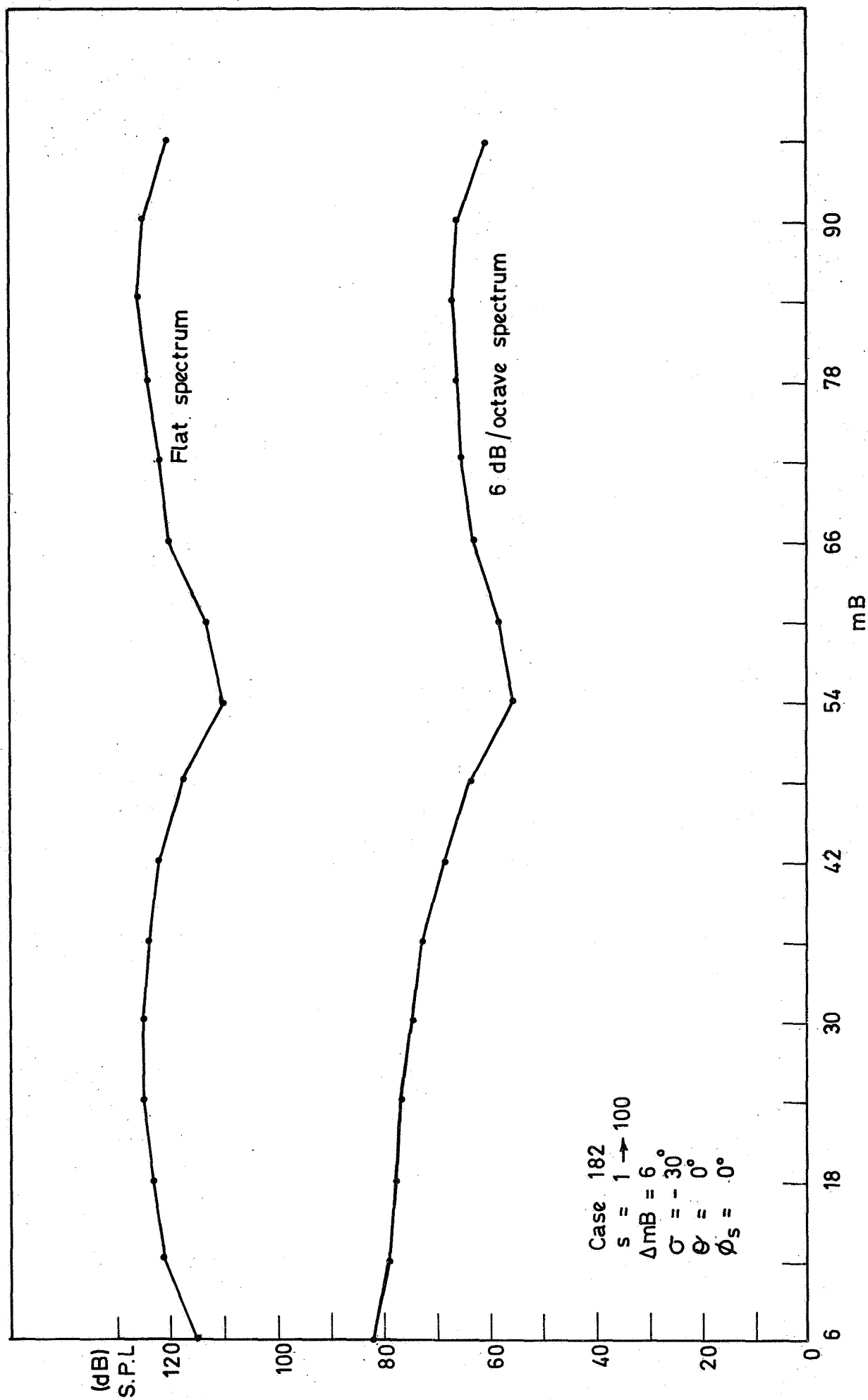


Fig.2.2.1 Continuous B.L.H. spectrum Effect of B.L.H. fall-off (Low res.)

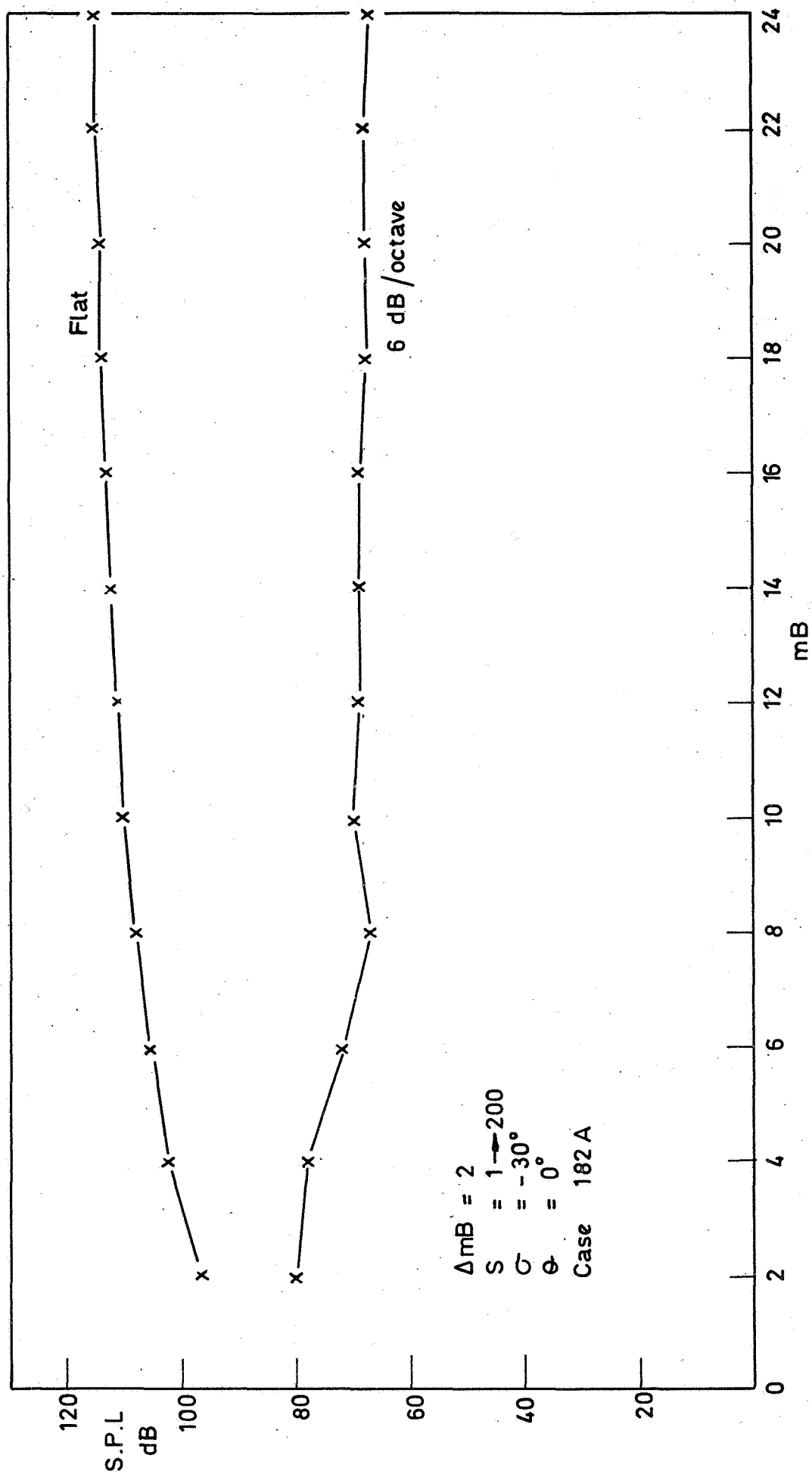


Fig.2.2.2. Continuous B.L.H. spectrum, effect of B.L.H fall-off (high res.)

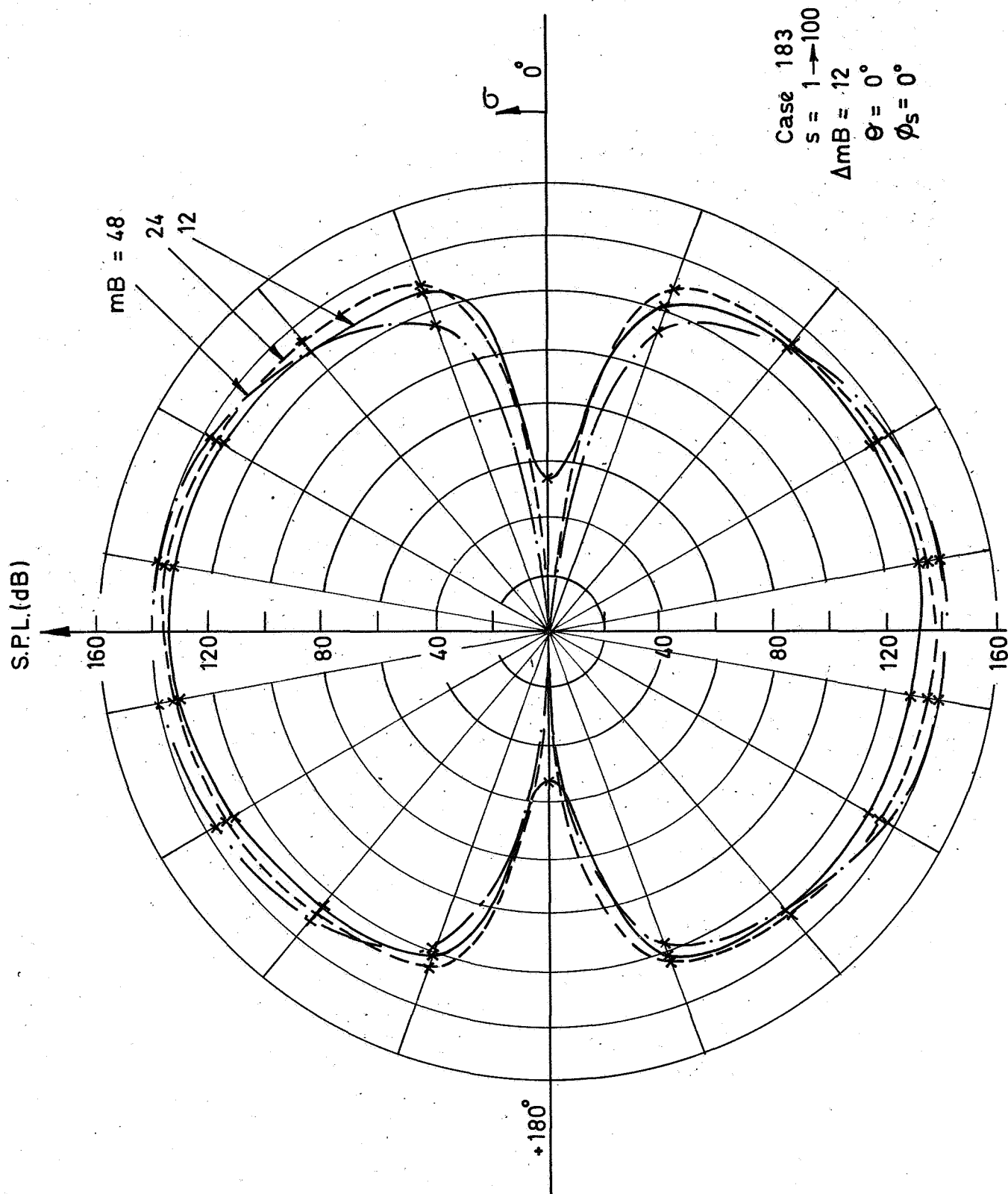


Fig. 2.2.3 Continuous B.L.H. spectrum Flat spectrum, polar elevation

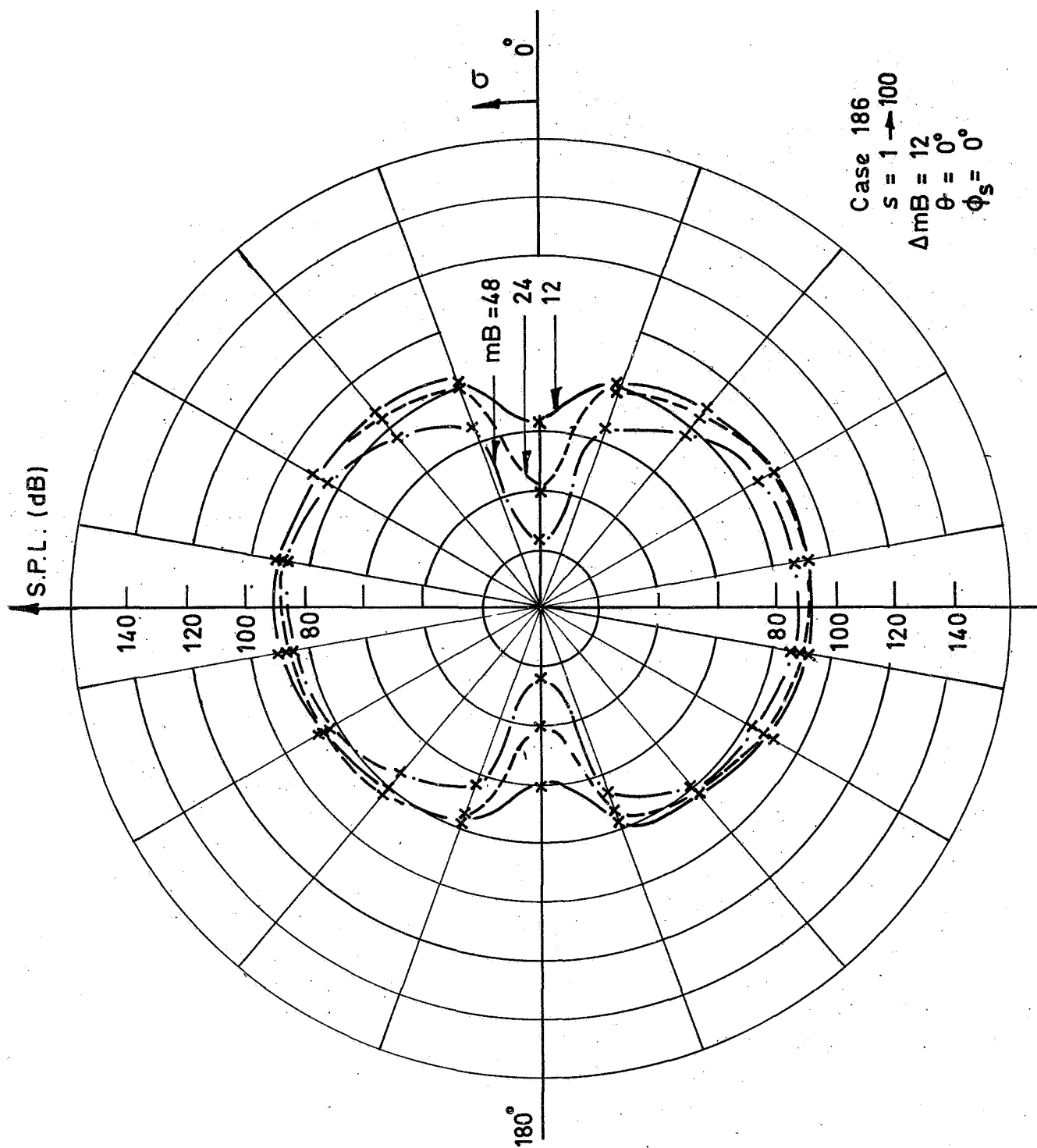


Fig. 2.2.4 Continuous B.L.H. spectrum . 6 dB / octave spectrum . Polar elevation .

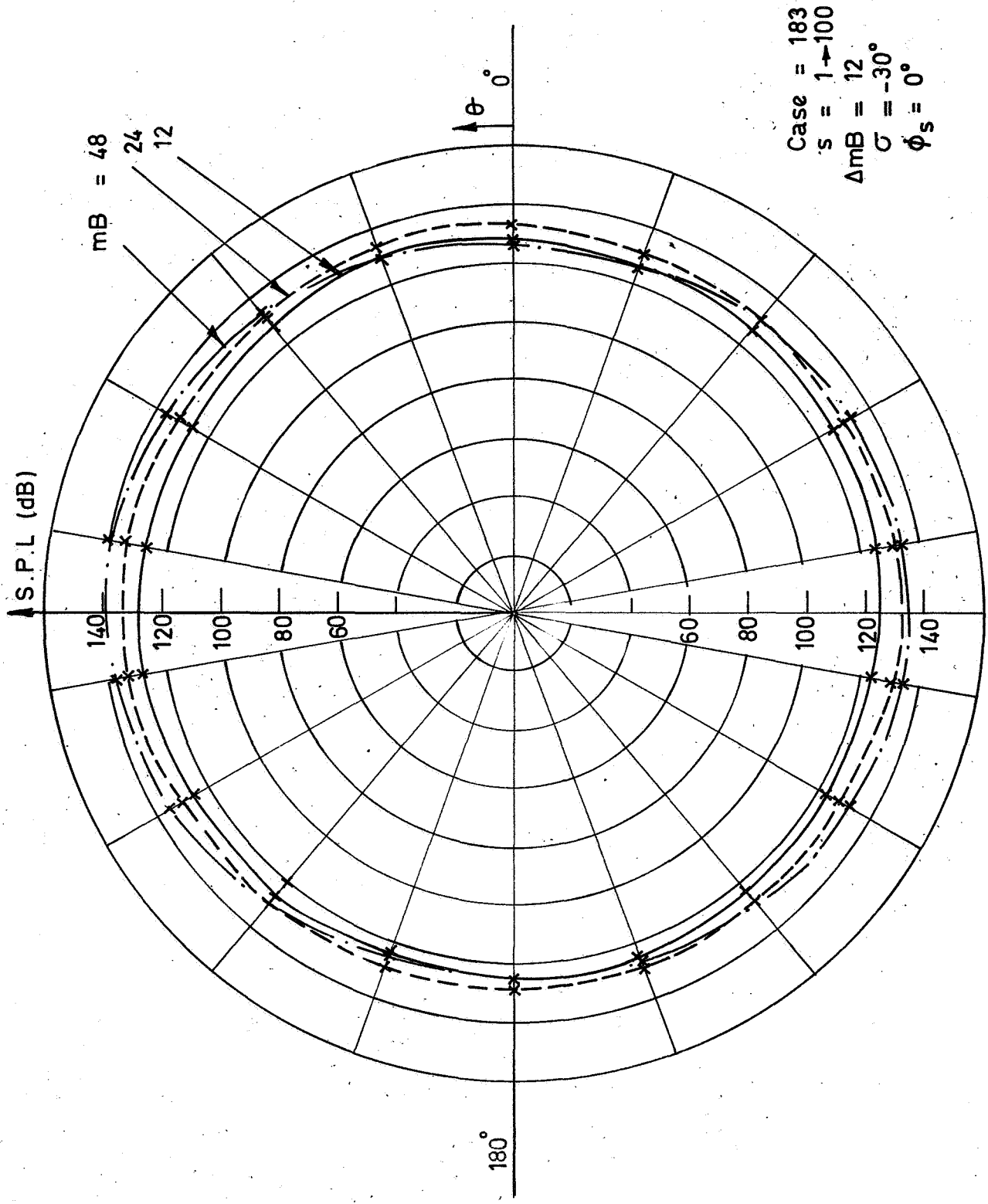


Fig.2.2.5 Continuous B.L.H. spectrum. Flat spectrum, Polar plan.

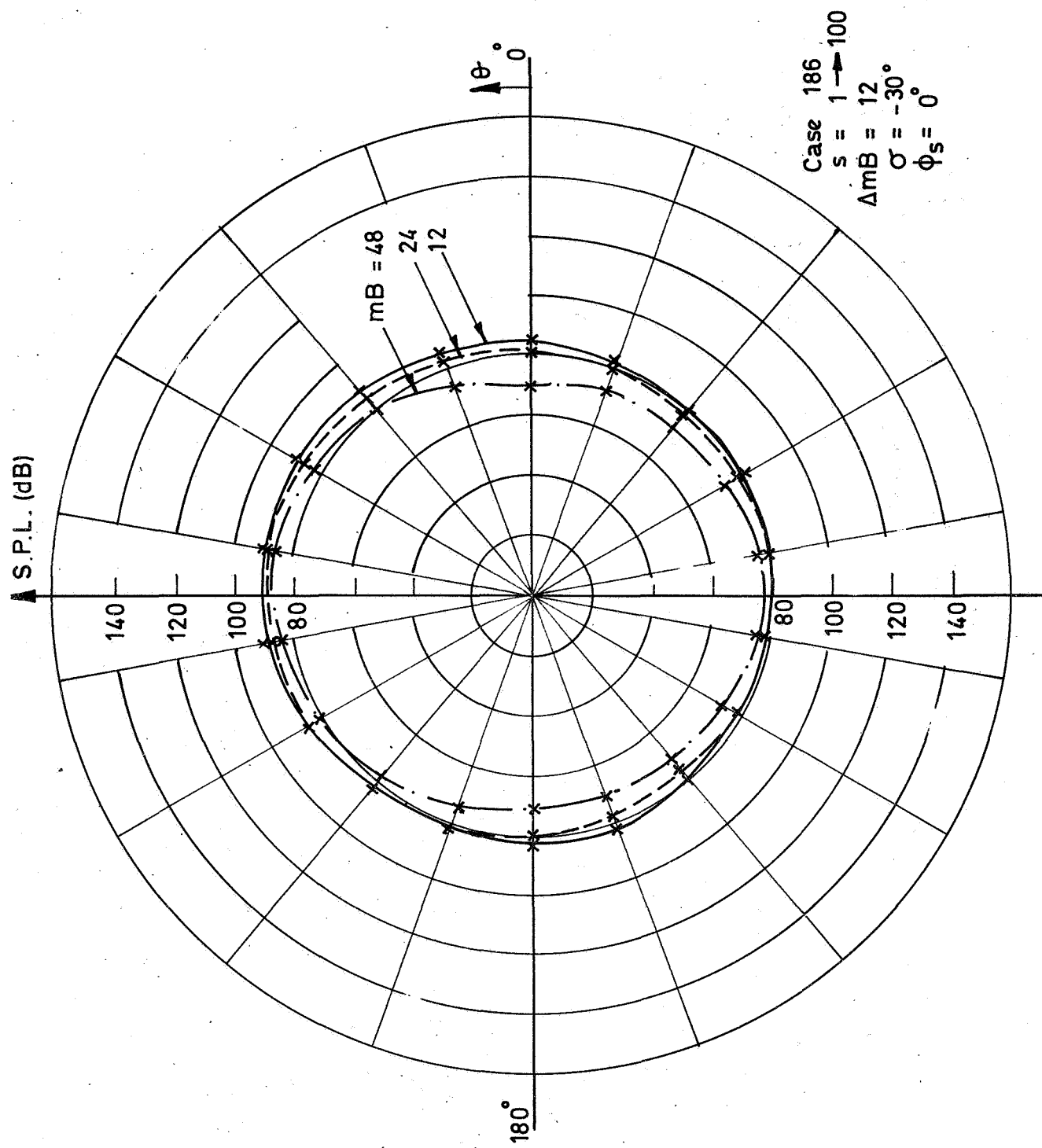


Fig 2.2.6 Continuous B.L.H spectrum . 6 dB/ octave spectrum . Polar plan

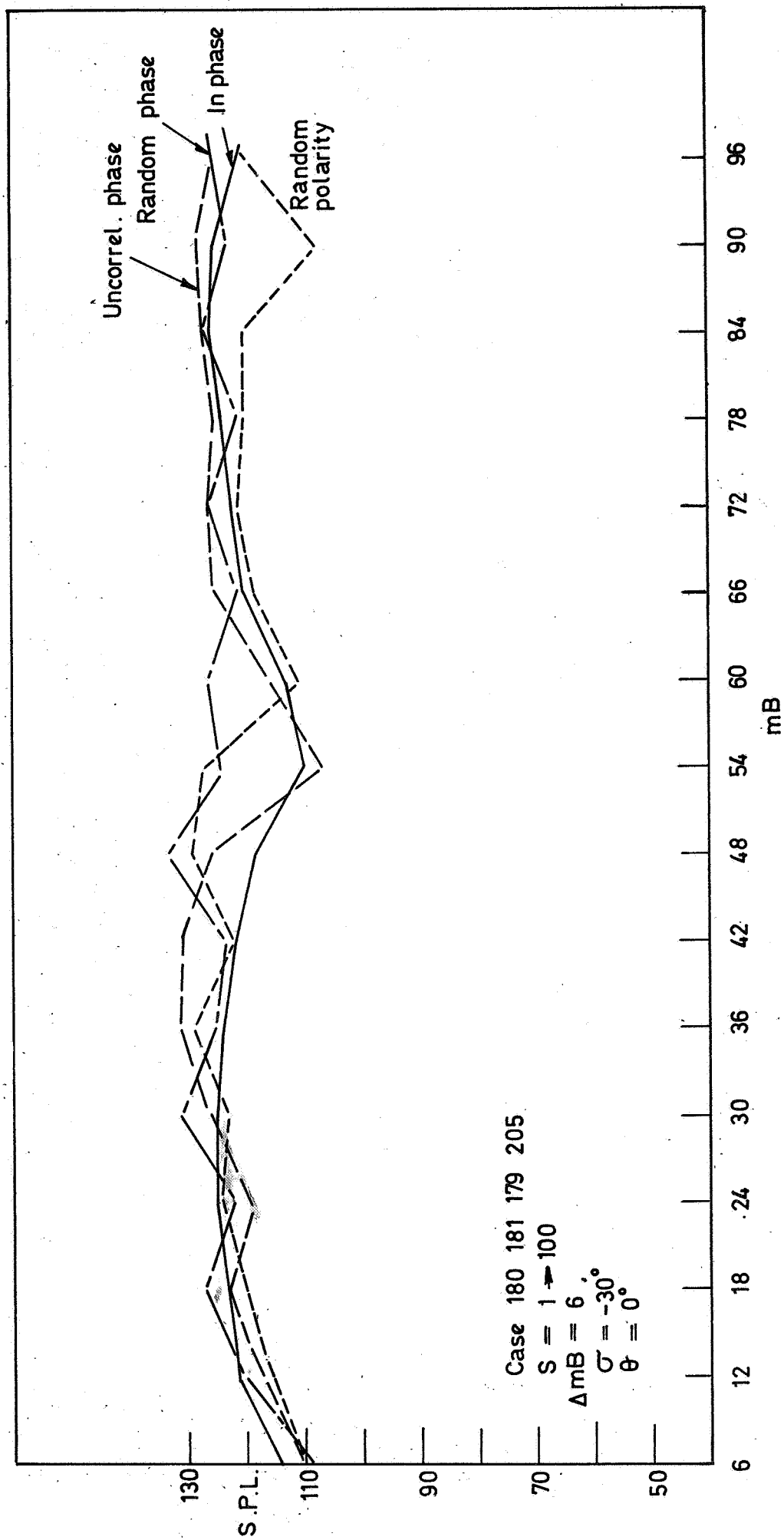


Fig .2.2.7. Continuous B.L. spectrum . Effect of B.L.H. phase ( flat spectrum )

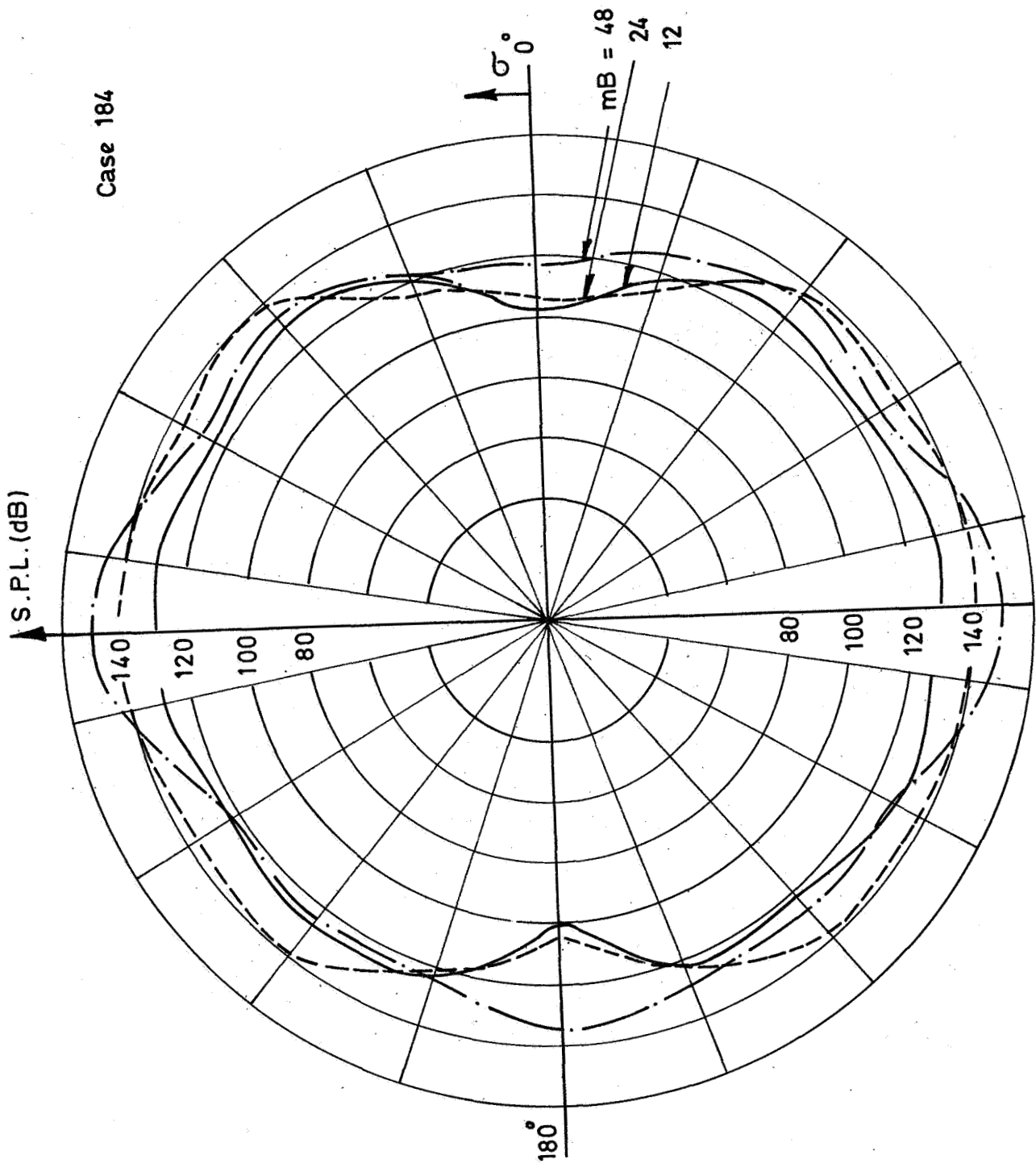


Fig.2.2.8 Continuous B.L. spectrum - random polarity Polar elevation  $\theta = 0^\circ$

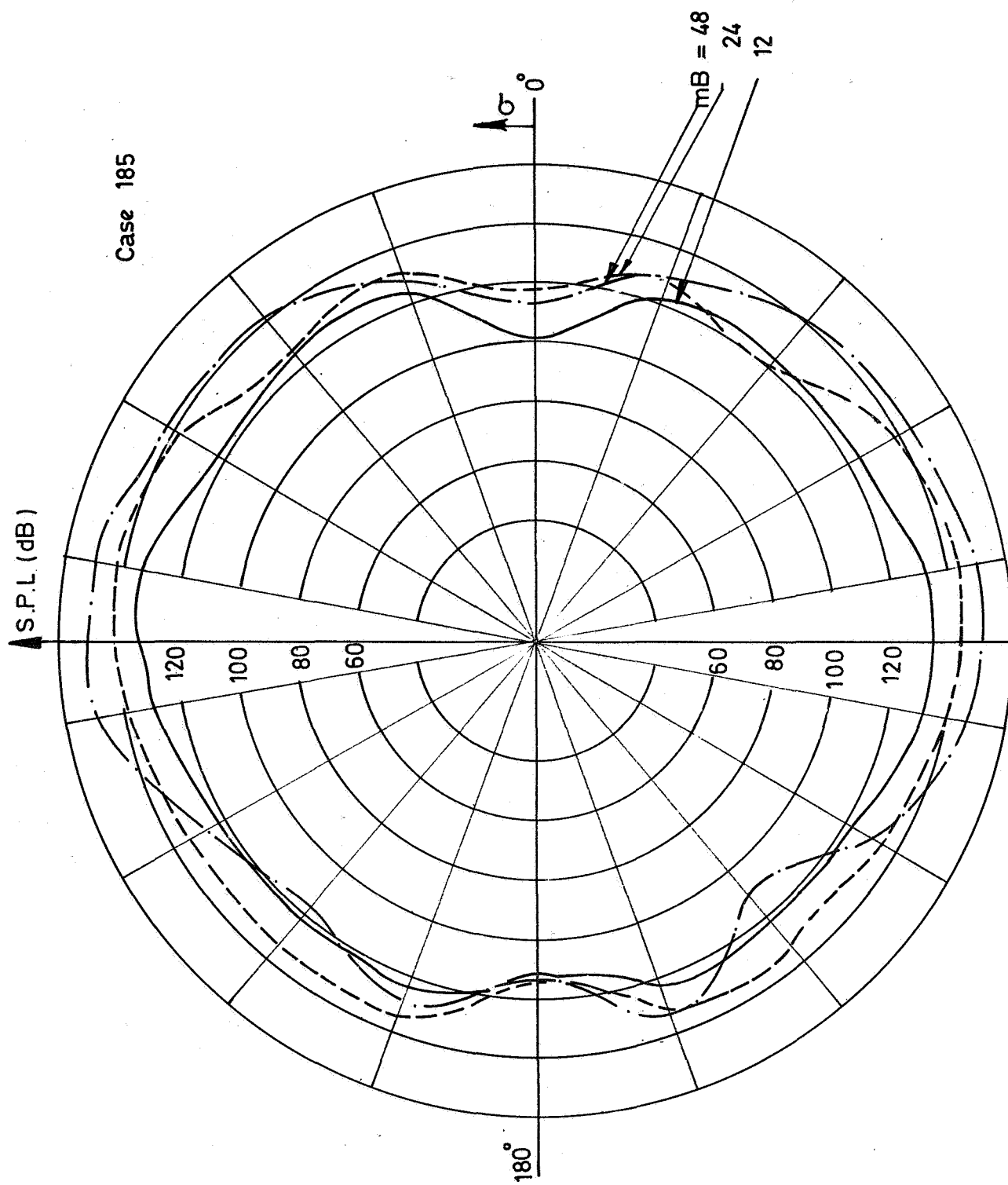


Fig.2.2.9 Continuous B.L spectrum - random phase Polar elevation  $\Theta = 0^\circ$

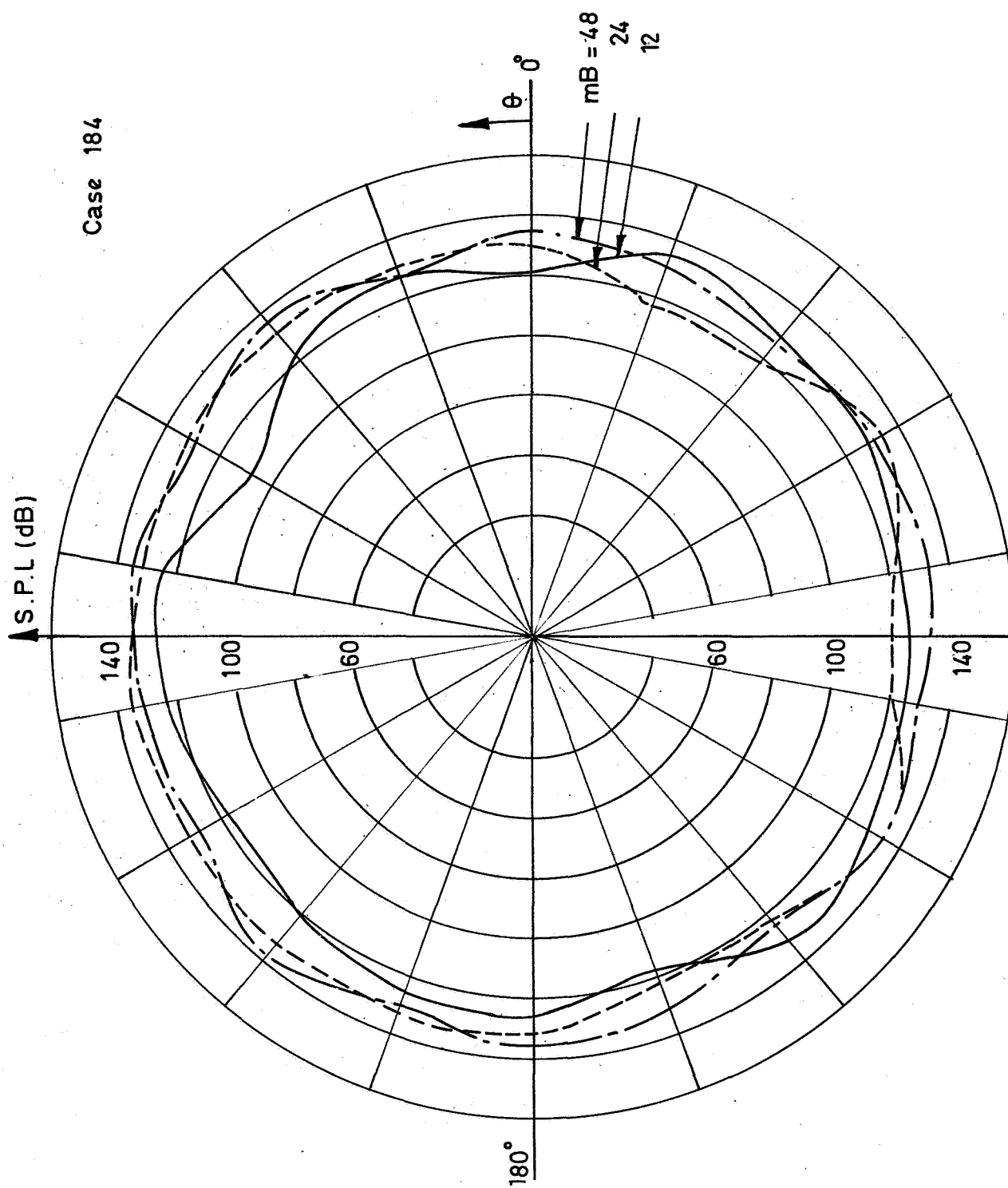


Fig 2.2.10 Continuous B.L spectrum - random polarity. Polar plan.  $\sigma = -30^\circ$

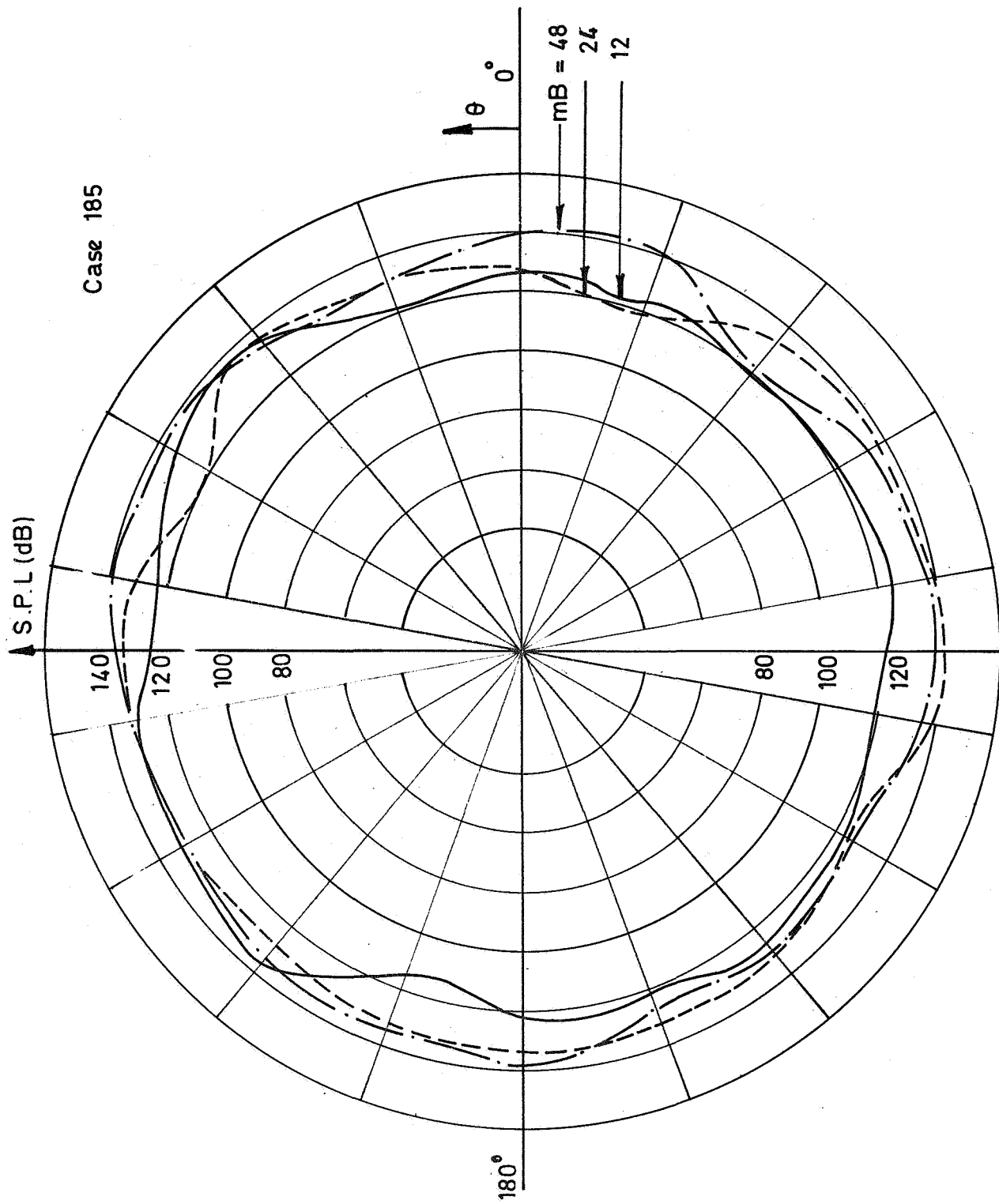


Fig.2.2.11 Continuous B.L spectrum - random phase . Polar plan,  $\sigma = -30^\circ$

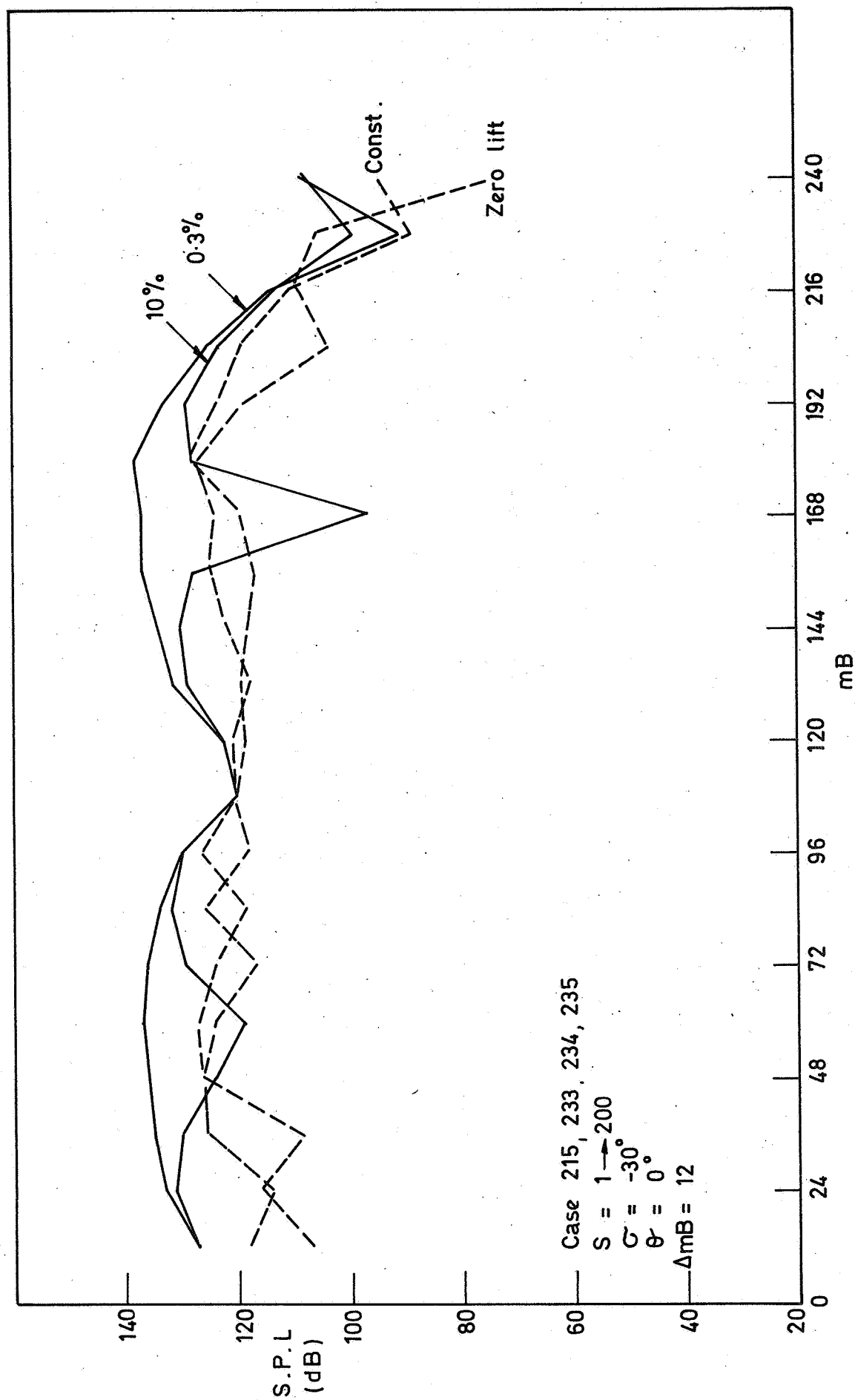


Fig.2.3.1.Flat B.L spectrum . Effect of span distribution . (Low res)

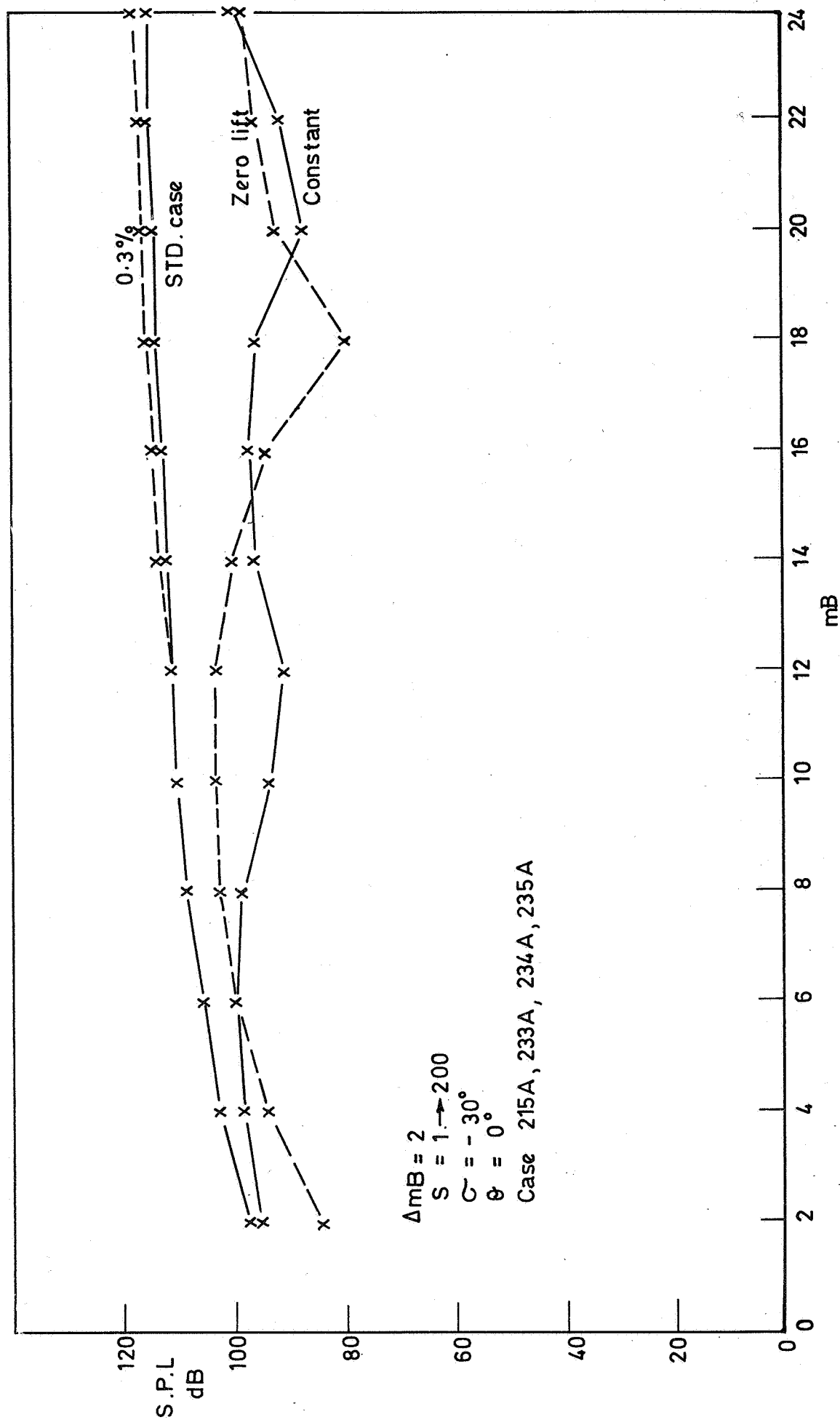


Fig. 2.3.2. Flat B.L. spectrum, effect of span distribution (high res.)

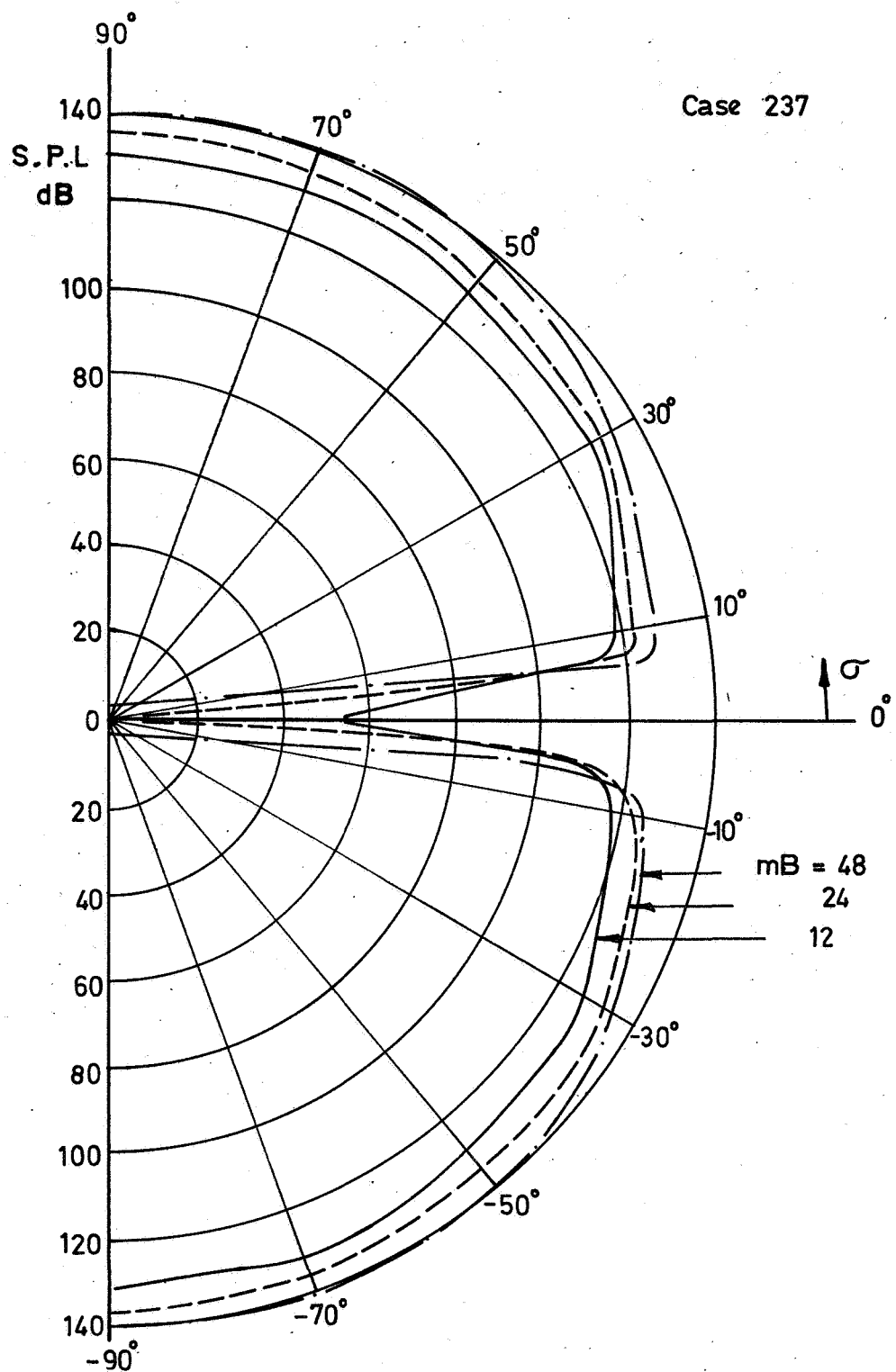


Fig 2.3.3. Flat B.L.spectrum Dist.= 0.3%. Polar elevation  $\Theta = 0^\circ$

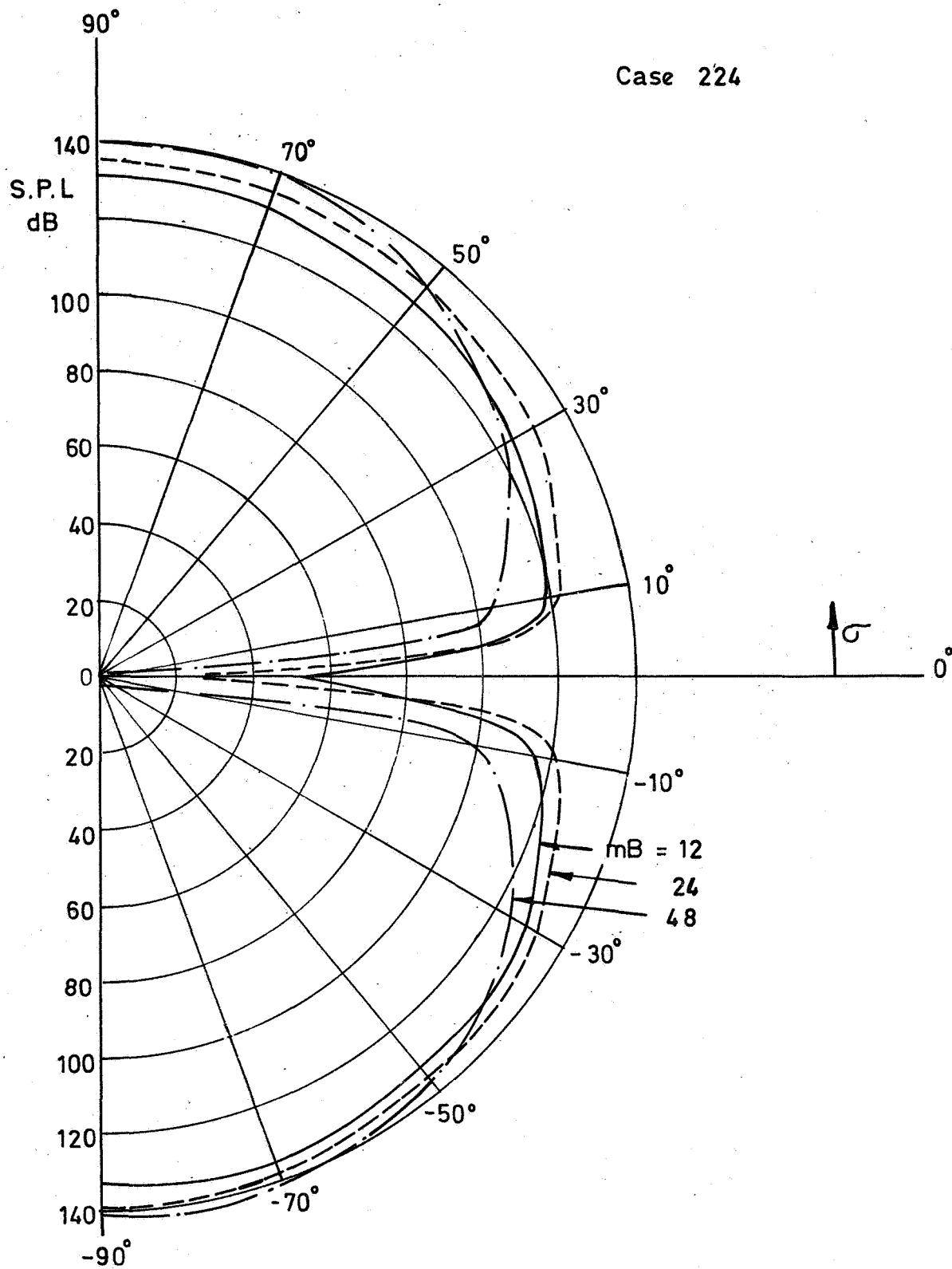


Fig. 2.3.4. Flat B.L.spectrum, std. case. Polar elevation  $\theta = 0^\circ$

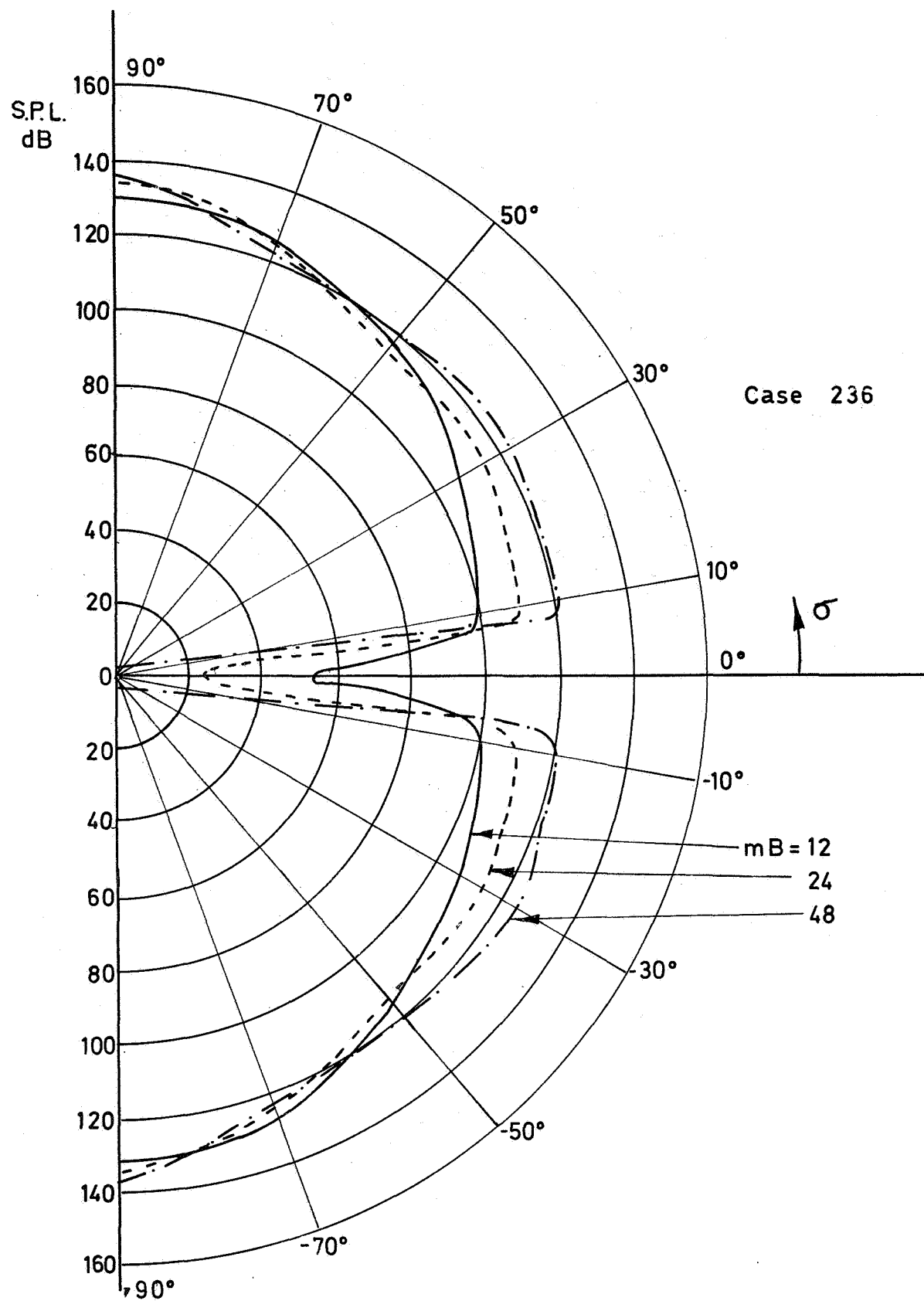


Fig. 2.3.5 Flat B.L.spectrum Dist = constant  
Polar elevation  $\theta = 0^\circ$

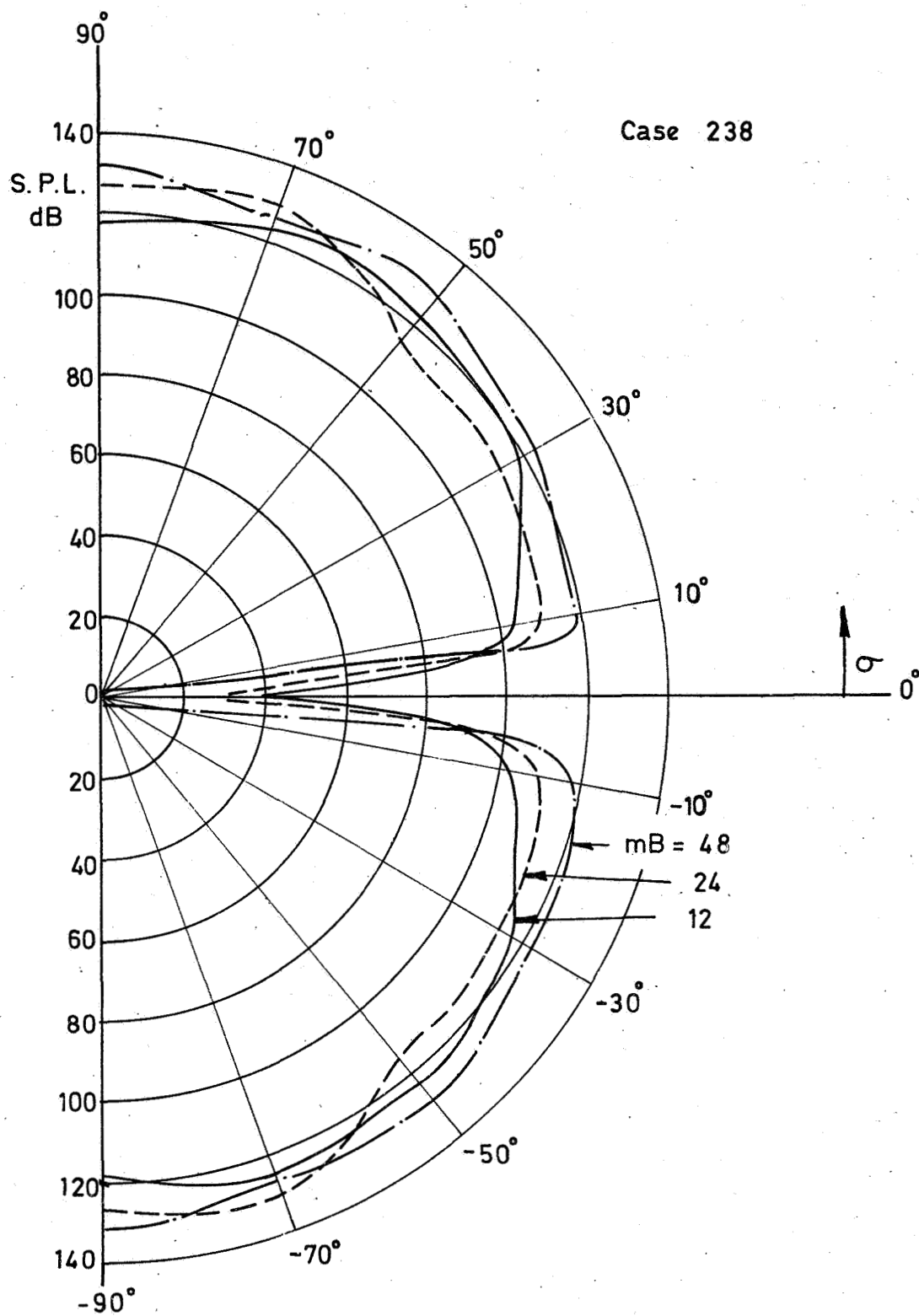


Fig. 2.3.6. Flat B.L. spectrum, Dist. = zero lift  
Polar elevation  $\theta = 0^\circ$

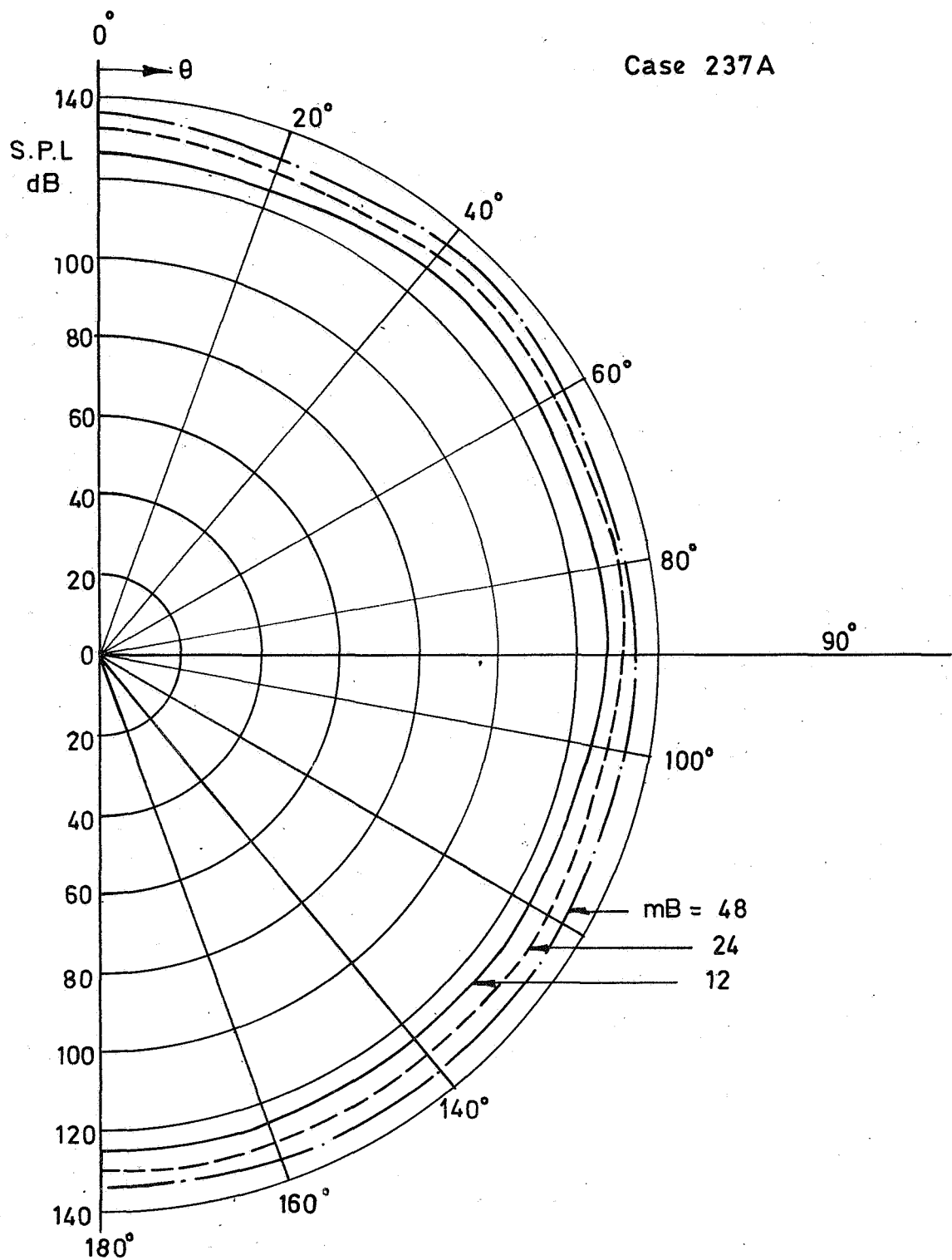


Fig. 2.3.7. Flat B.L. spectrum, Dist. = Rect. 0.3%  
Polar plan  $\sigma = -30^\circ$

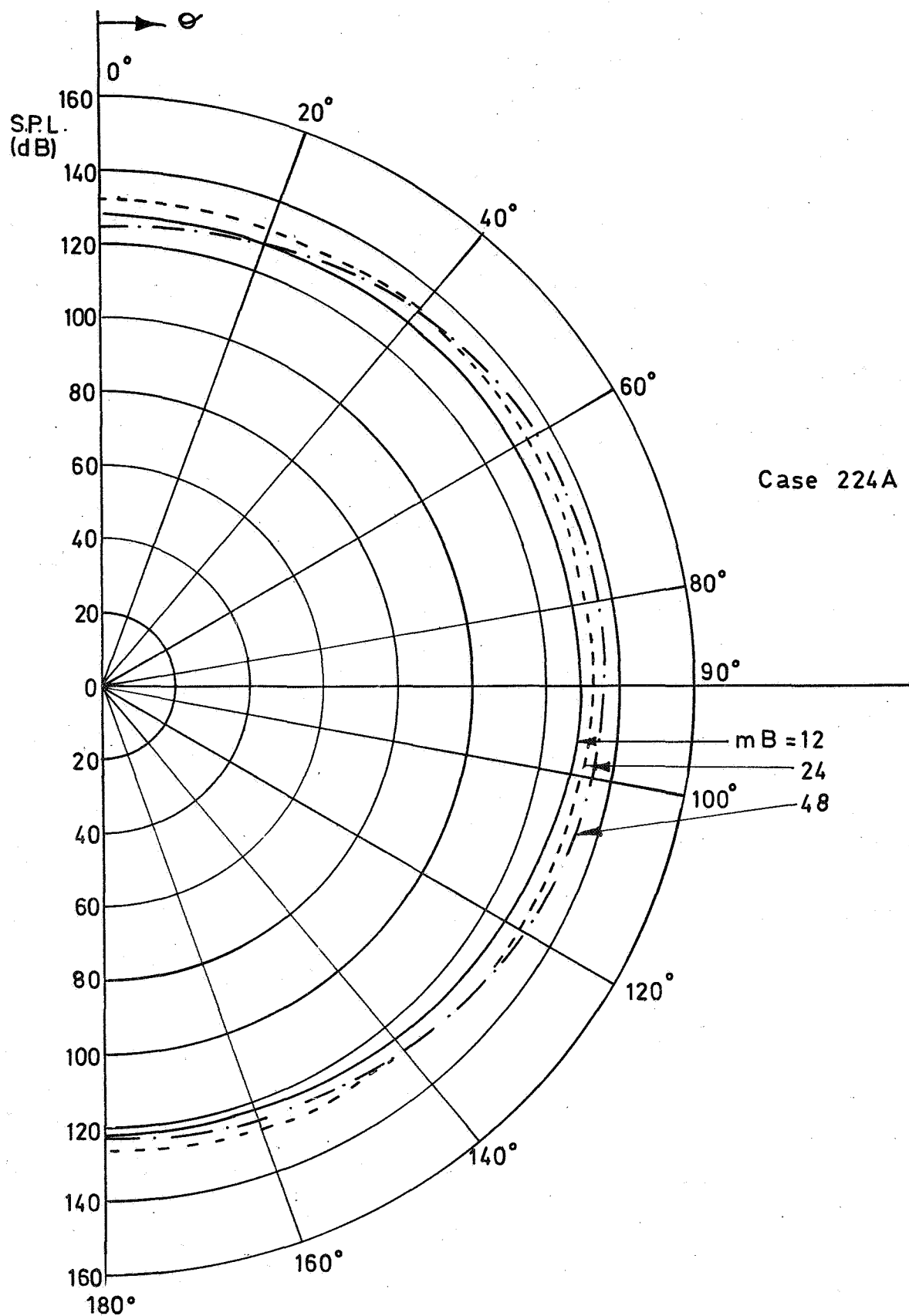


Fig. 2.3.8 Flat B.L. Spectrum std. case Polar plan  
 $\sigma = -30^\circ$

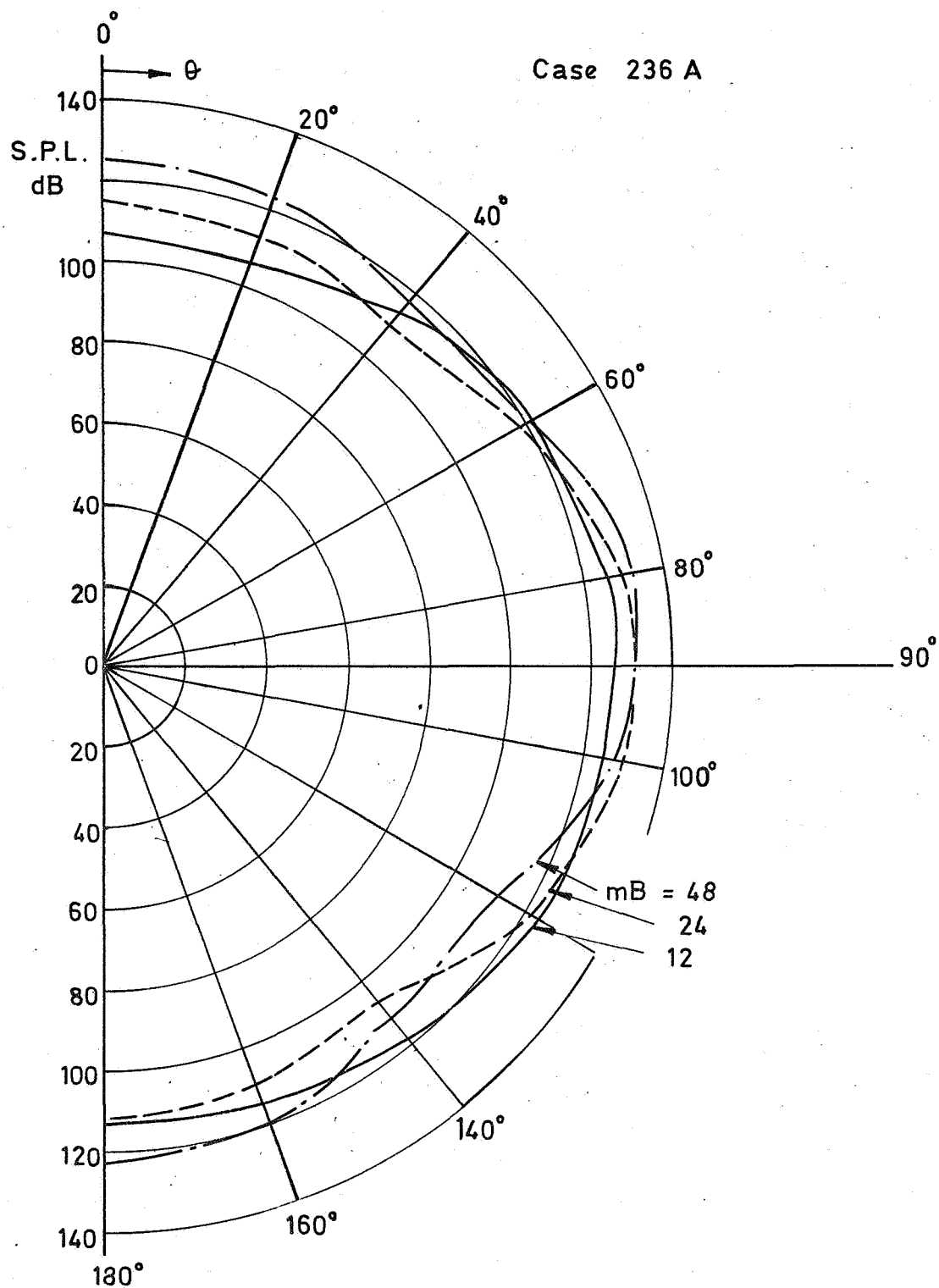


Fig.2.3.9 Flat B.L. spectrum, Dist. = const. Polar plan  
 $\sigma = -30^\circ$

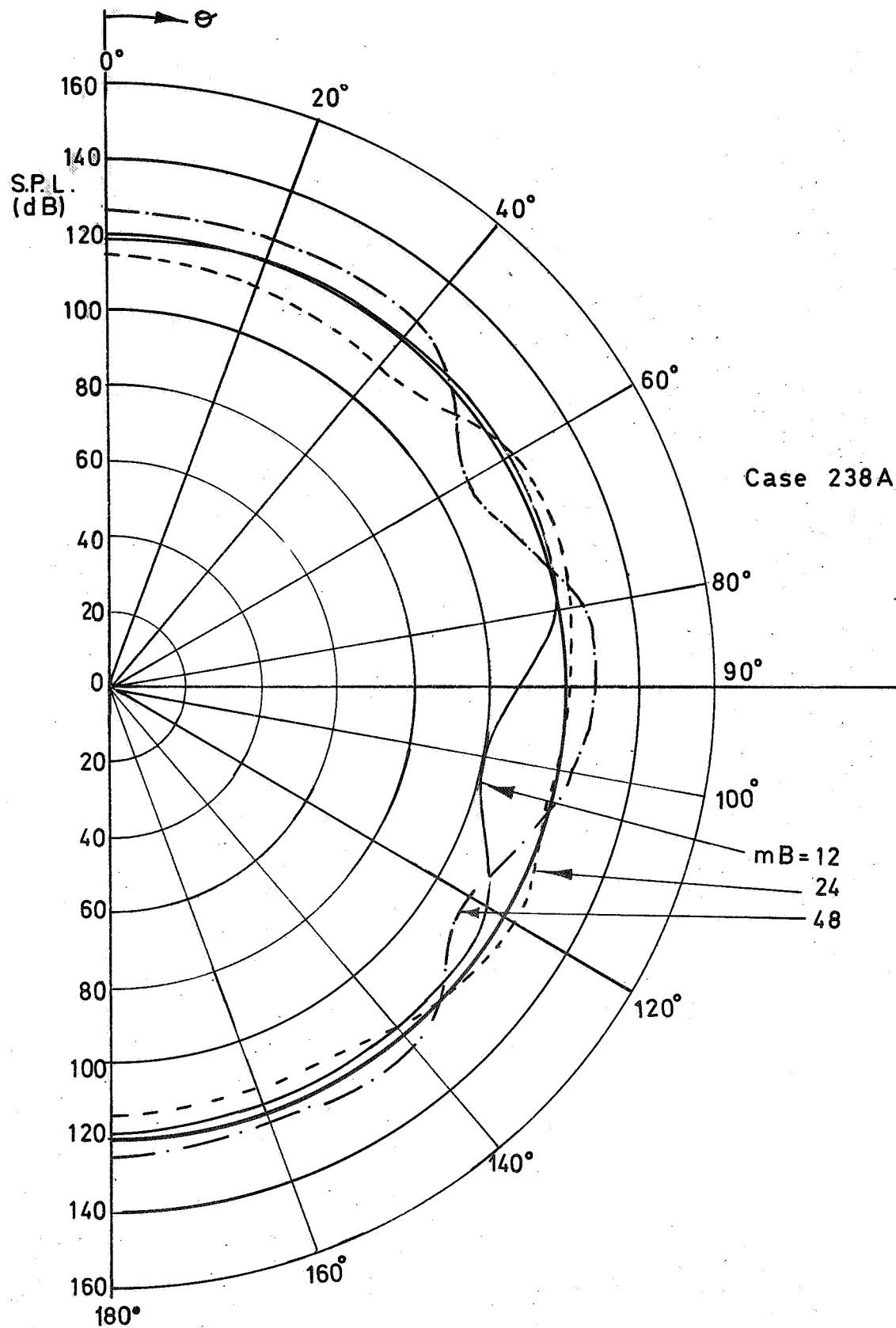


Fig. 2.3.10 Flat B.L. spectrum. Dist = zero lift.  
Polar plan  $\sigma = -30^\circ$

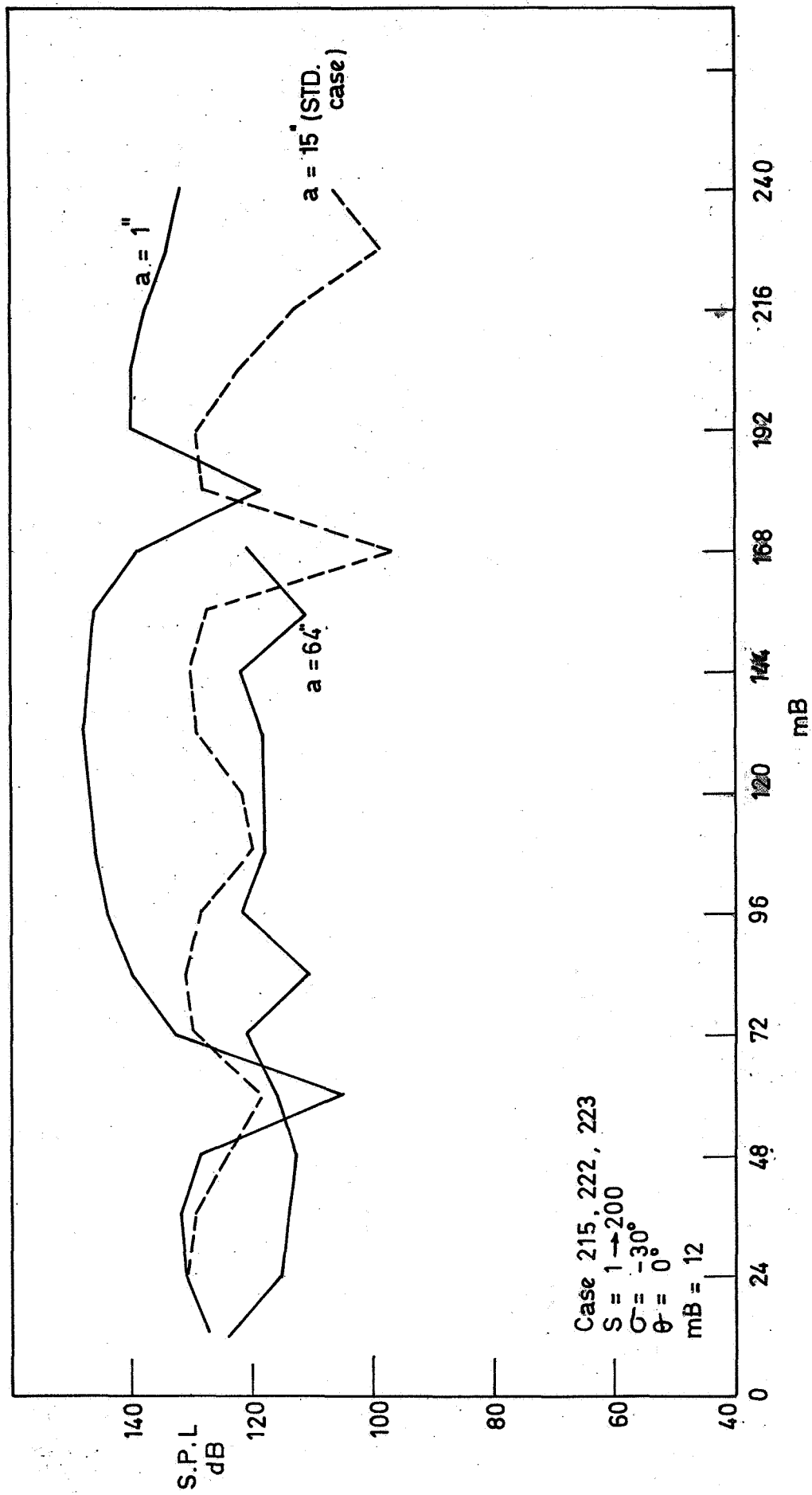


Fig. 2.3.11. Flat B.L. spectrum. Effect of chord width. (Low res.)

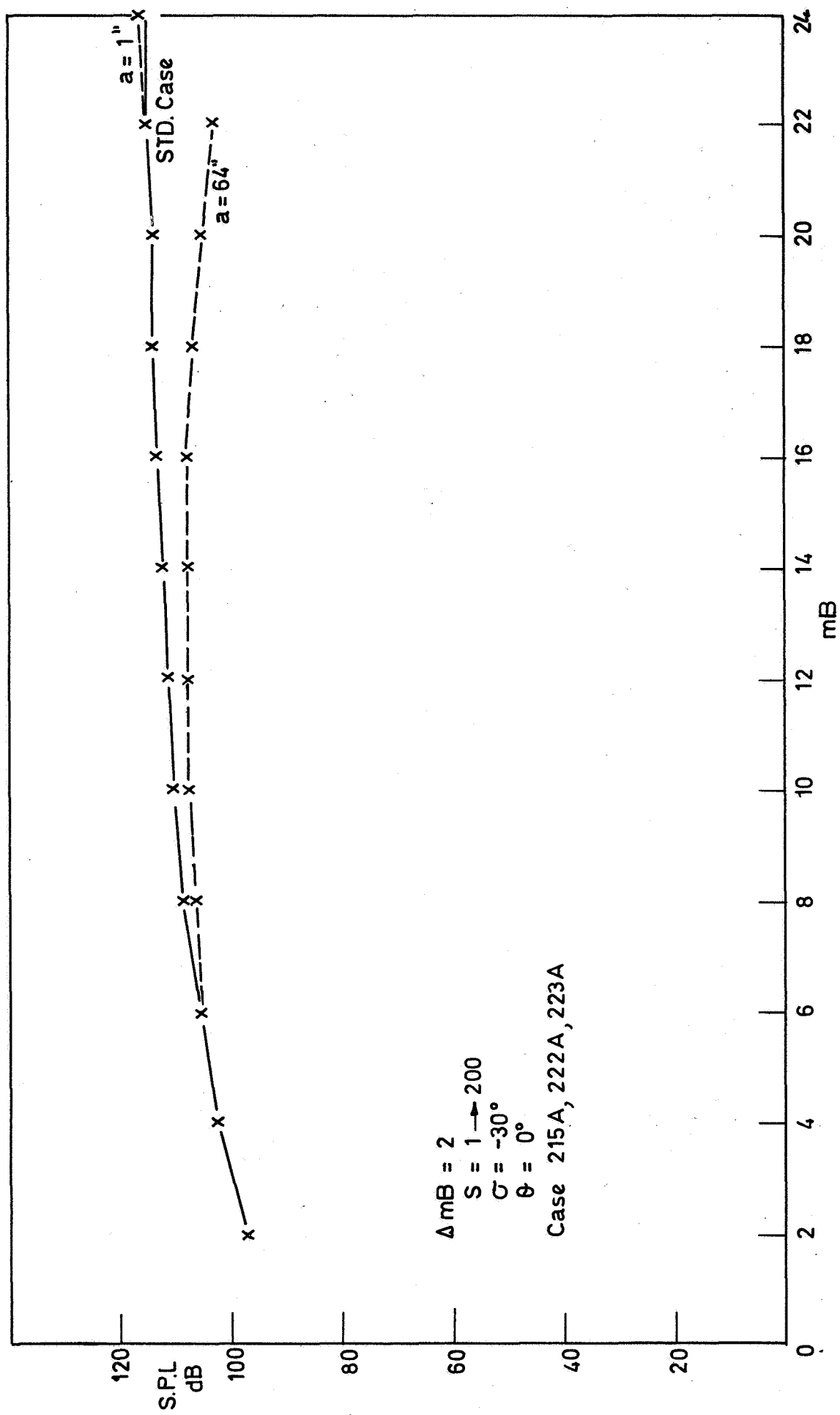


Fig. 2.3.12. Flat B.L. spectrum, effect of chord width (high res.)

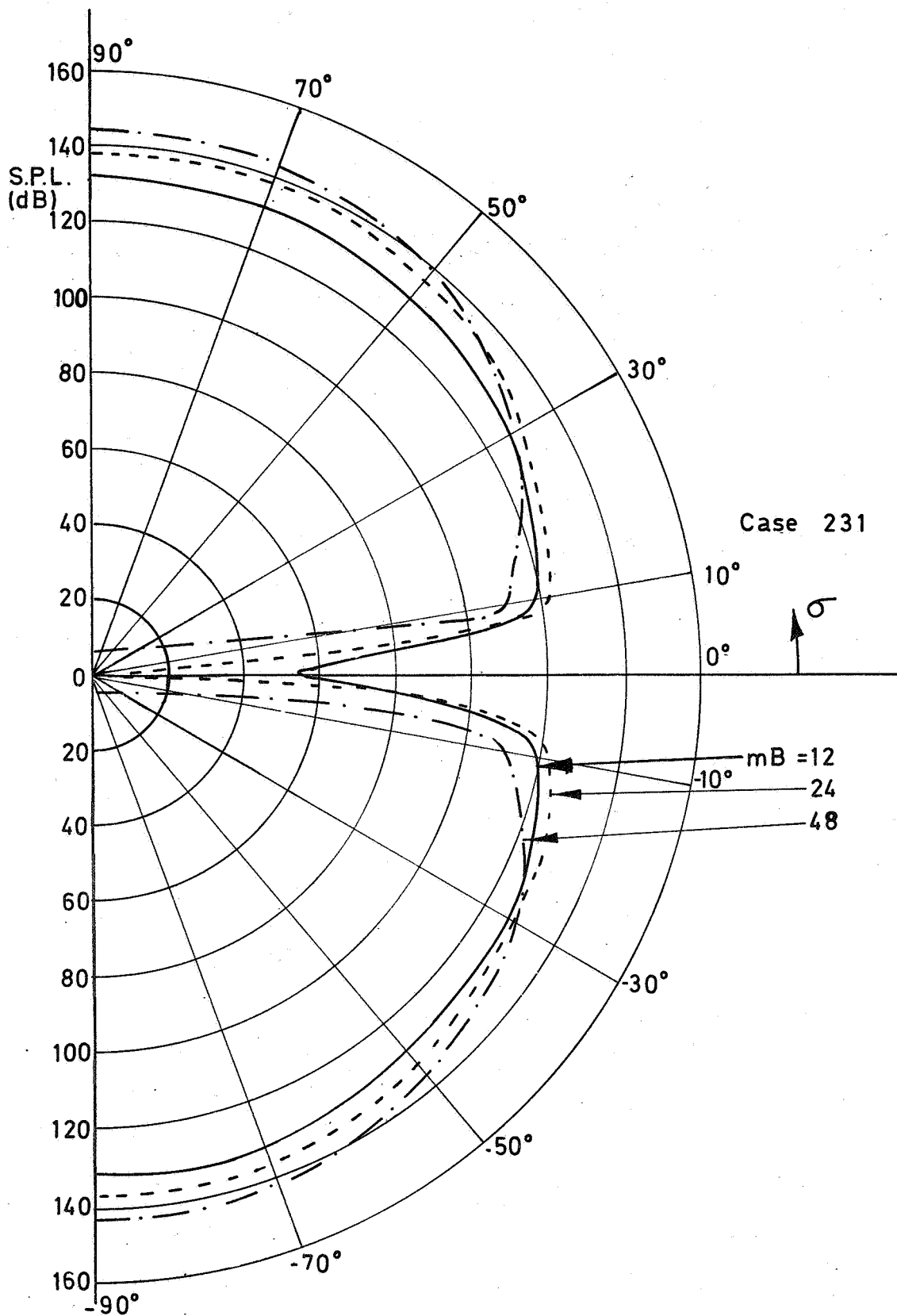


Fig. 2.3.13 Flat B.L. spectrum  $a=1''$  polar elevation  $\varphi=0^\circ$

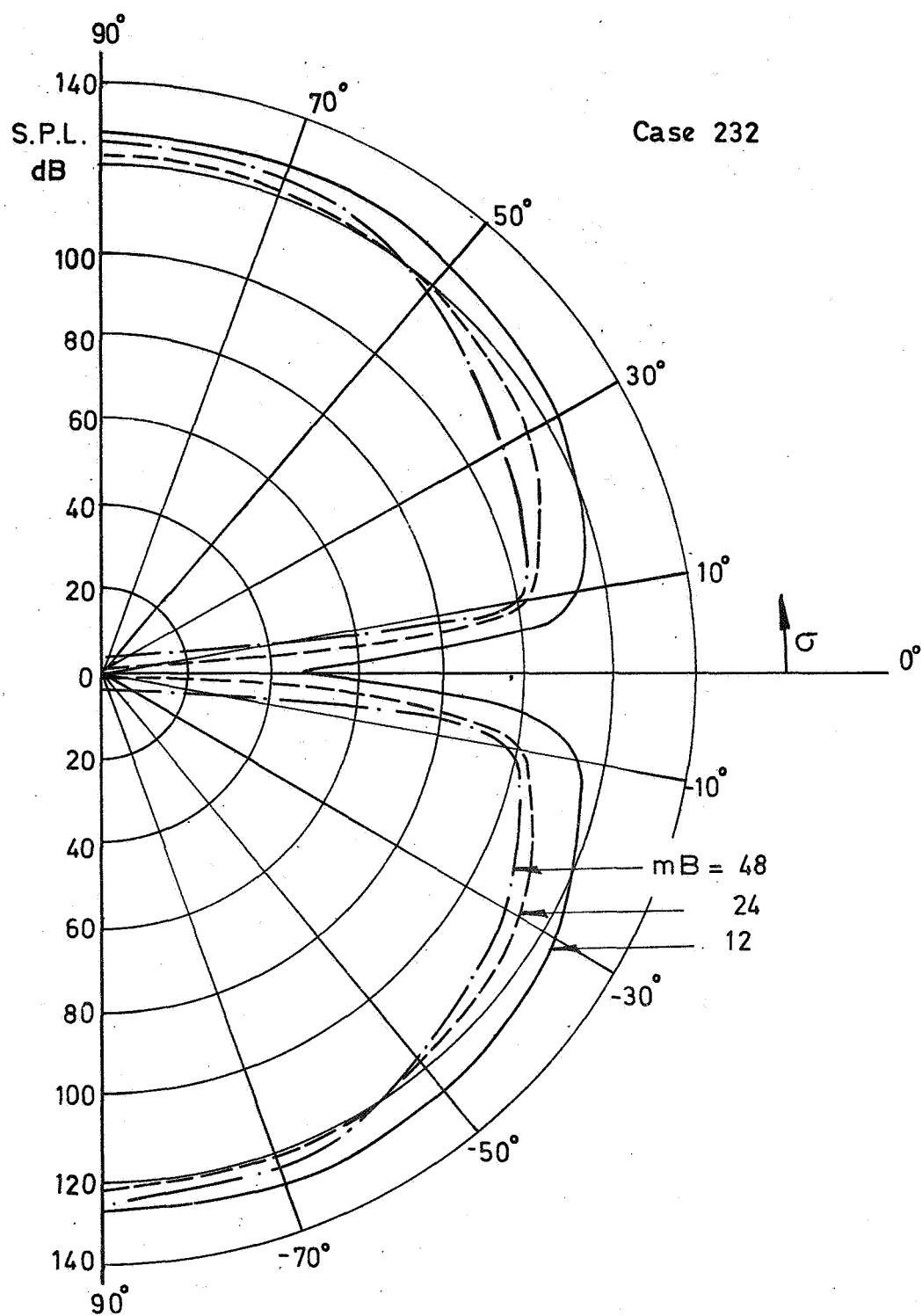


Fig. 2.3.14. Flat B.L. spectrum .  $a = 64''$  . Polar elevation .  $\theta = 0^\circ$

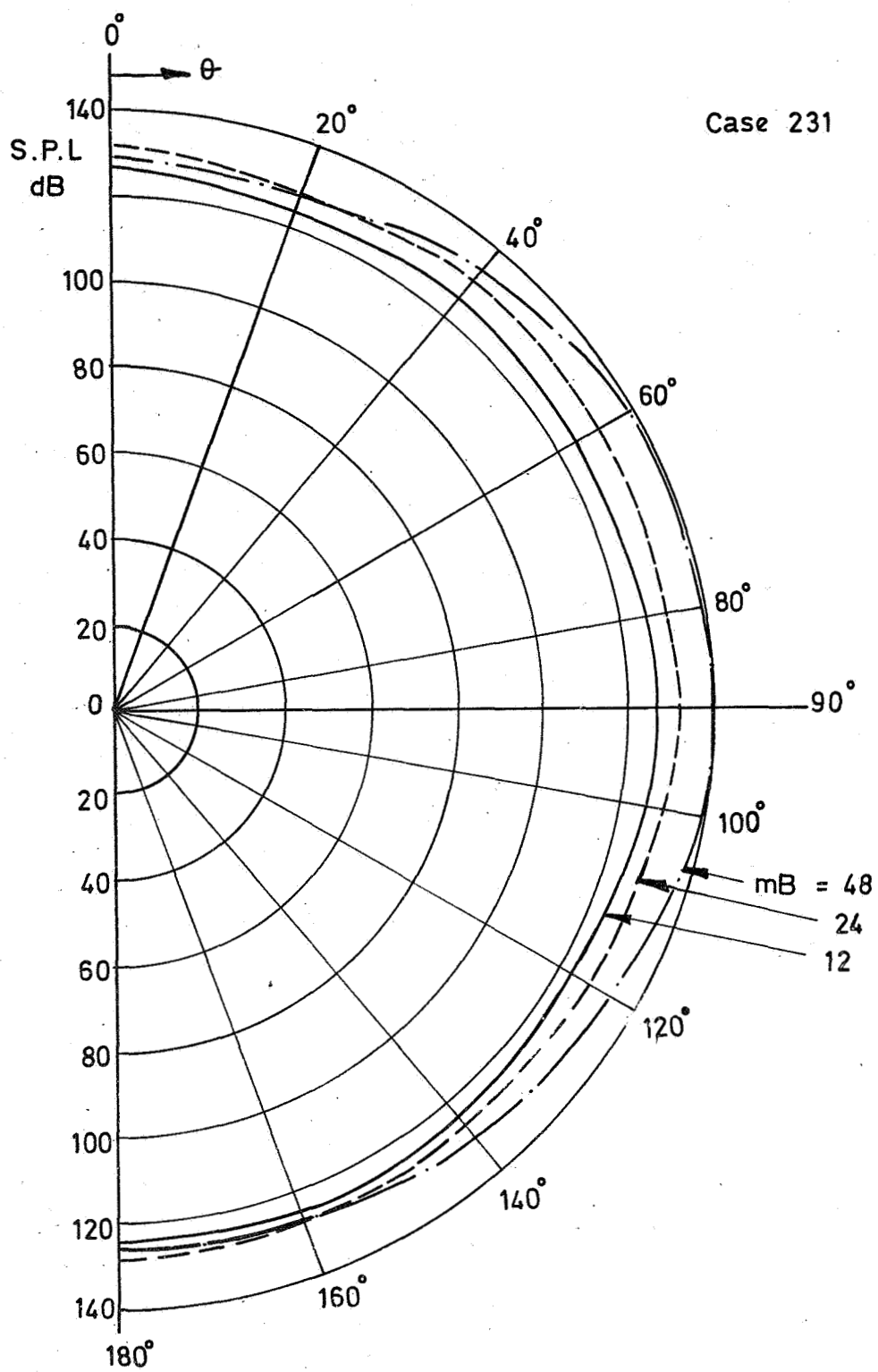


Fig. 2.3.15. Flat B.L spectrum.  $a = 1''$  Polar plan.  $\sigma = -30^\circ$

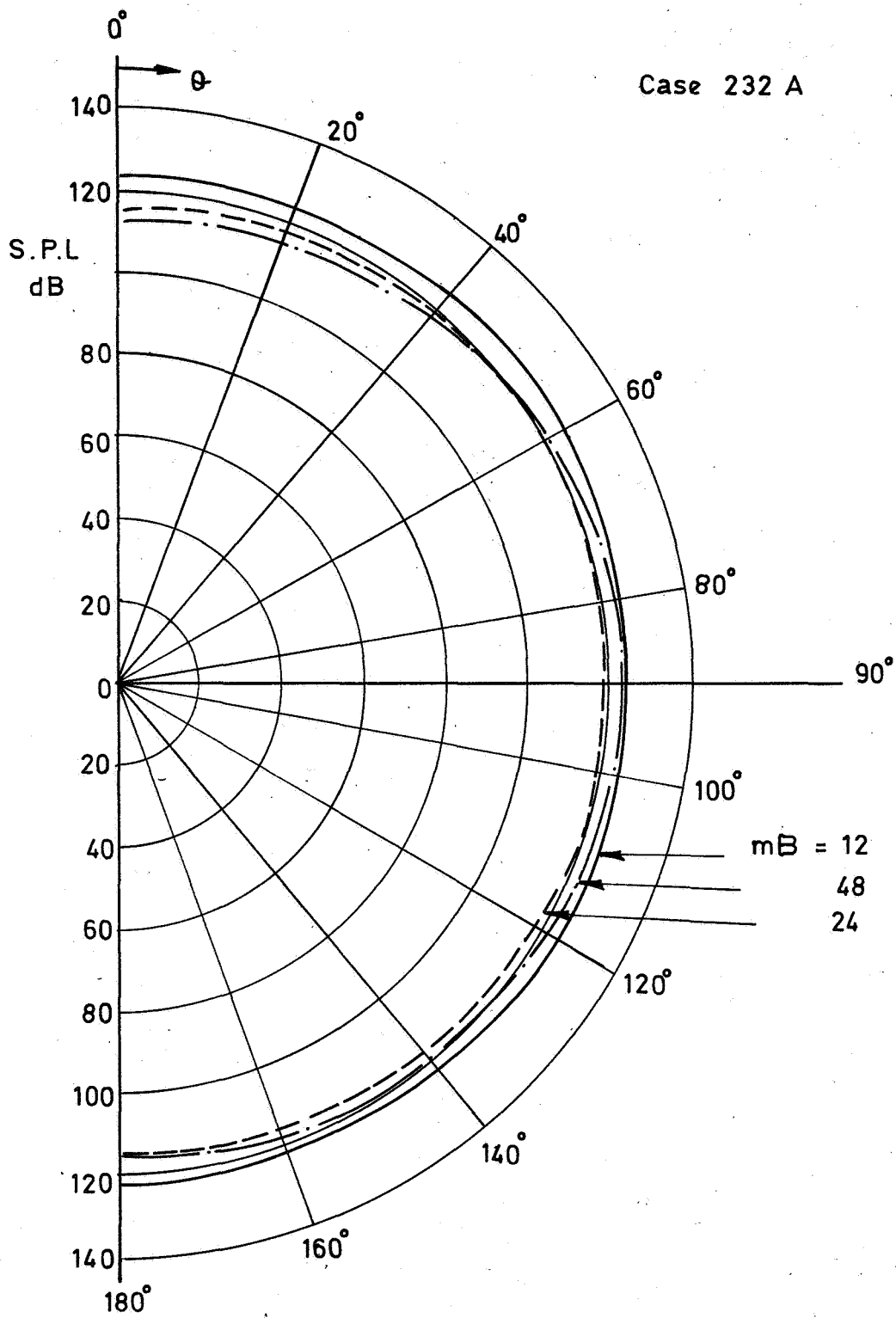


Fig. 2.3.16. Flat B.L. spectrum .  $a = 64''$  Polar plan  $\sigma = 30^\circ$

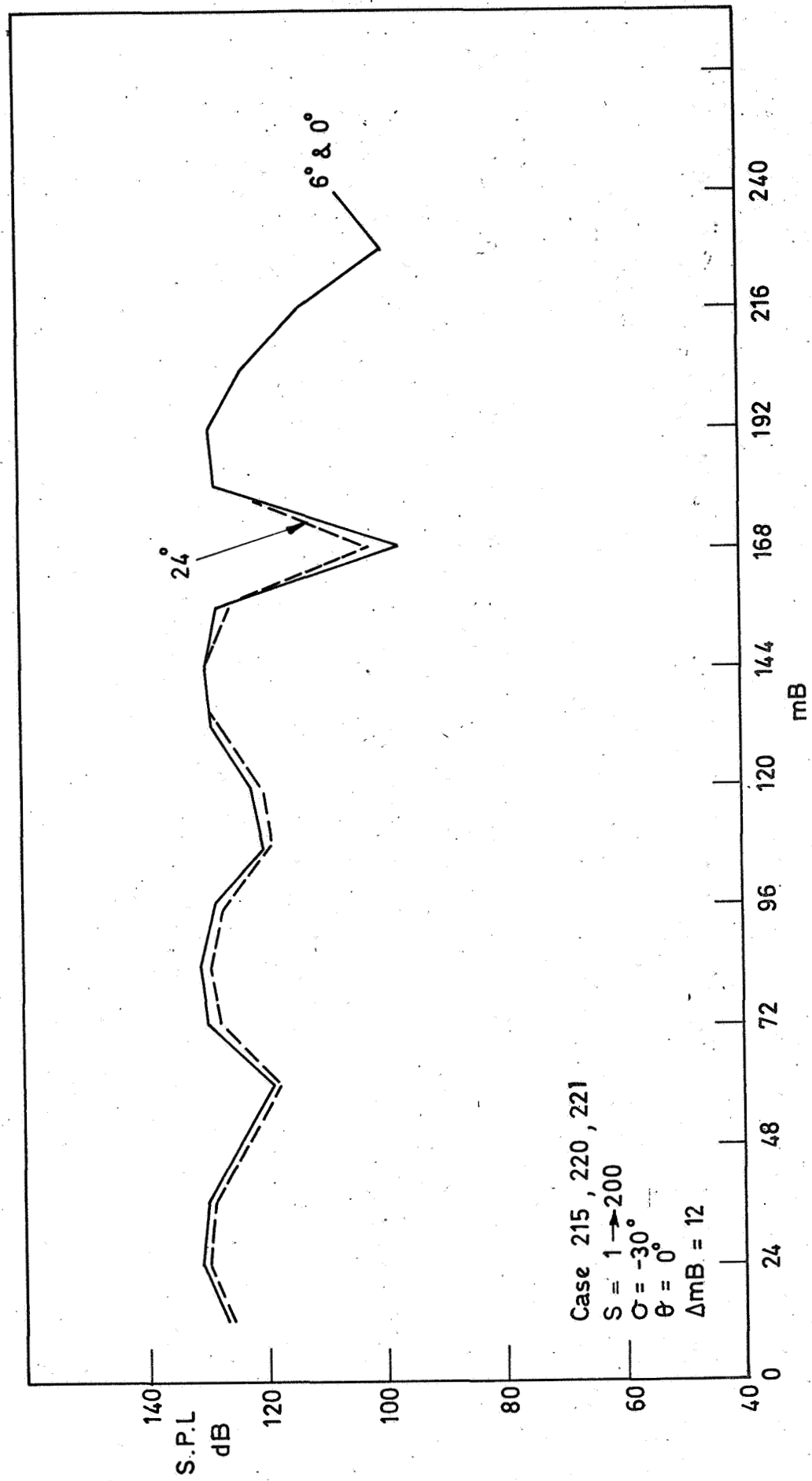


Fig 2.3.17 Flat B.L. spectrum. Effect of force angle (Low res)

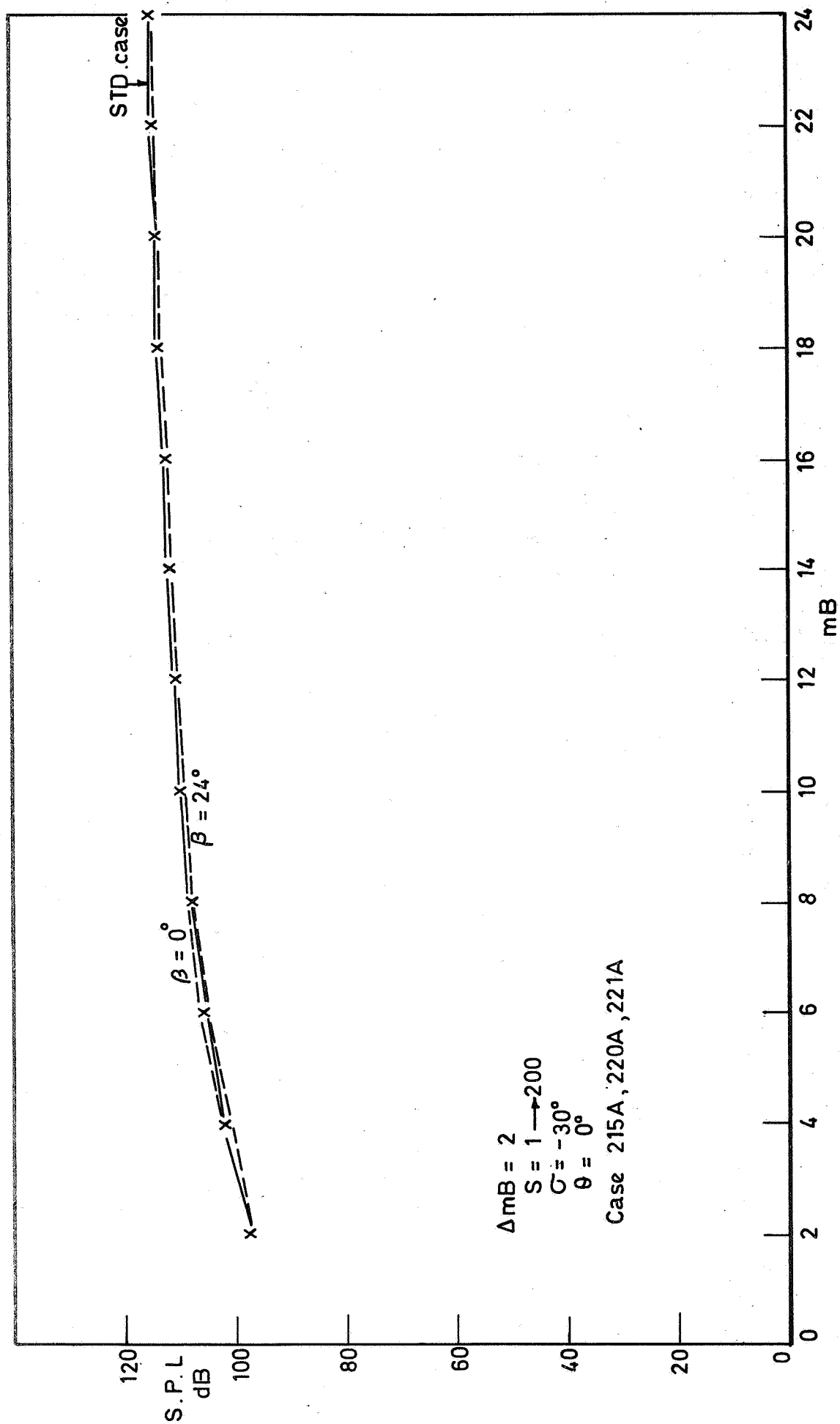


Fig. 2.3.18. Flat B.L. spectrum, effect of force angle (high res.)

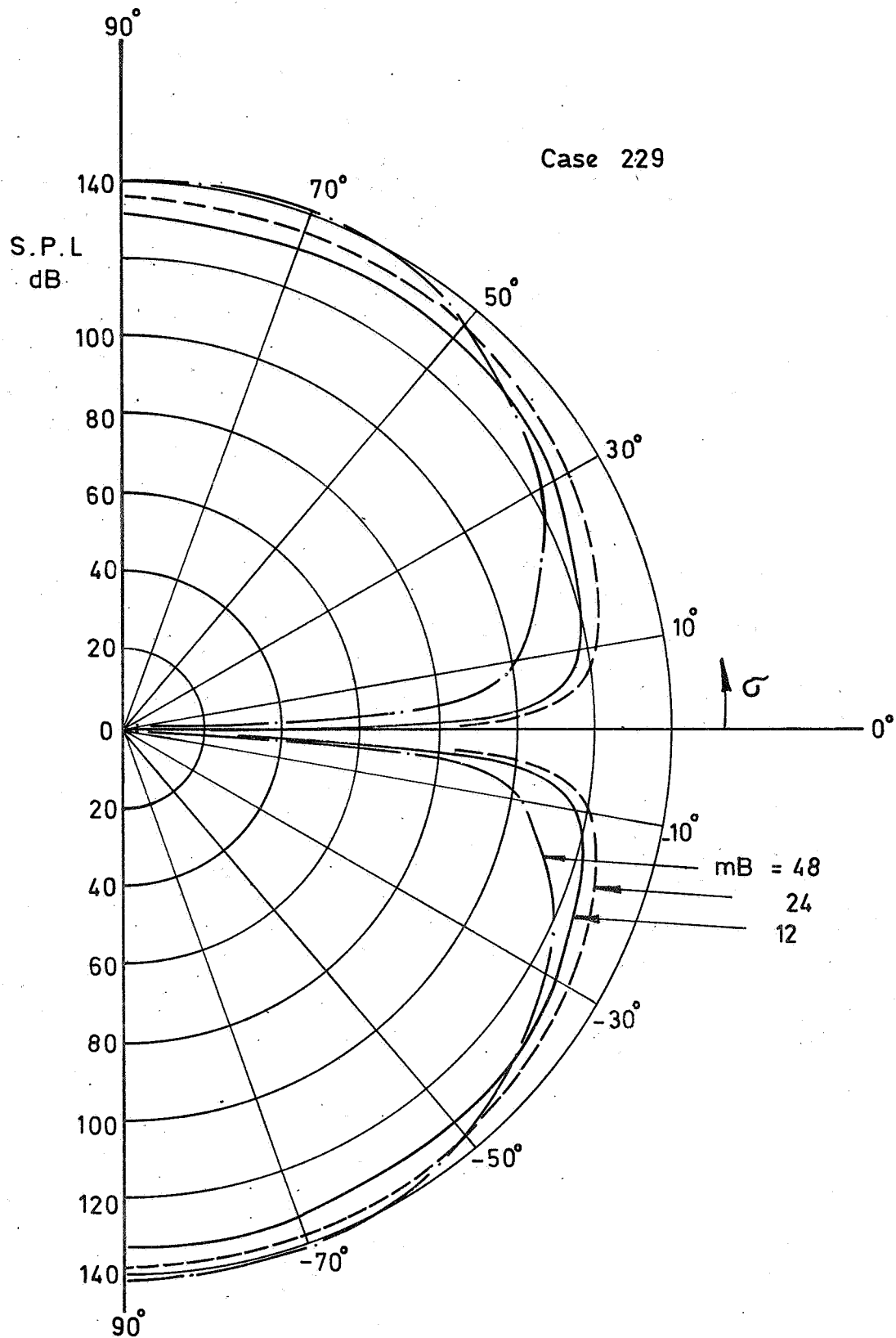


Fig. 2.3.19 Flat B.L. spectrum  $\beta = 0^\circ$ . Polar elevation  $\Theta = 0^\circ$

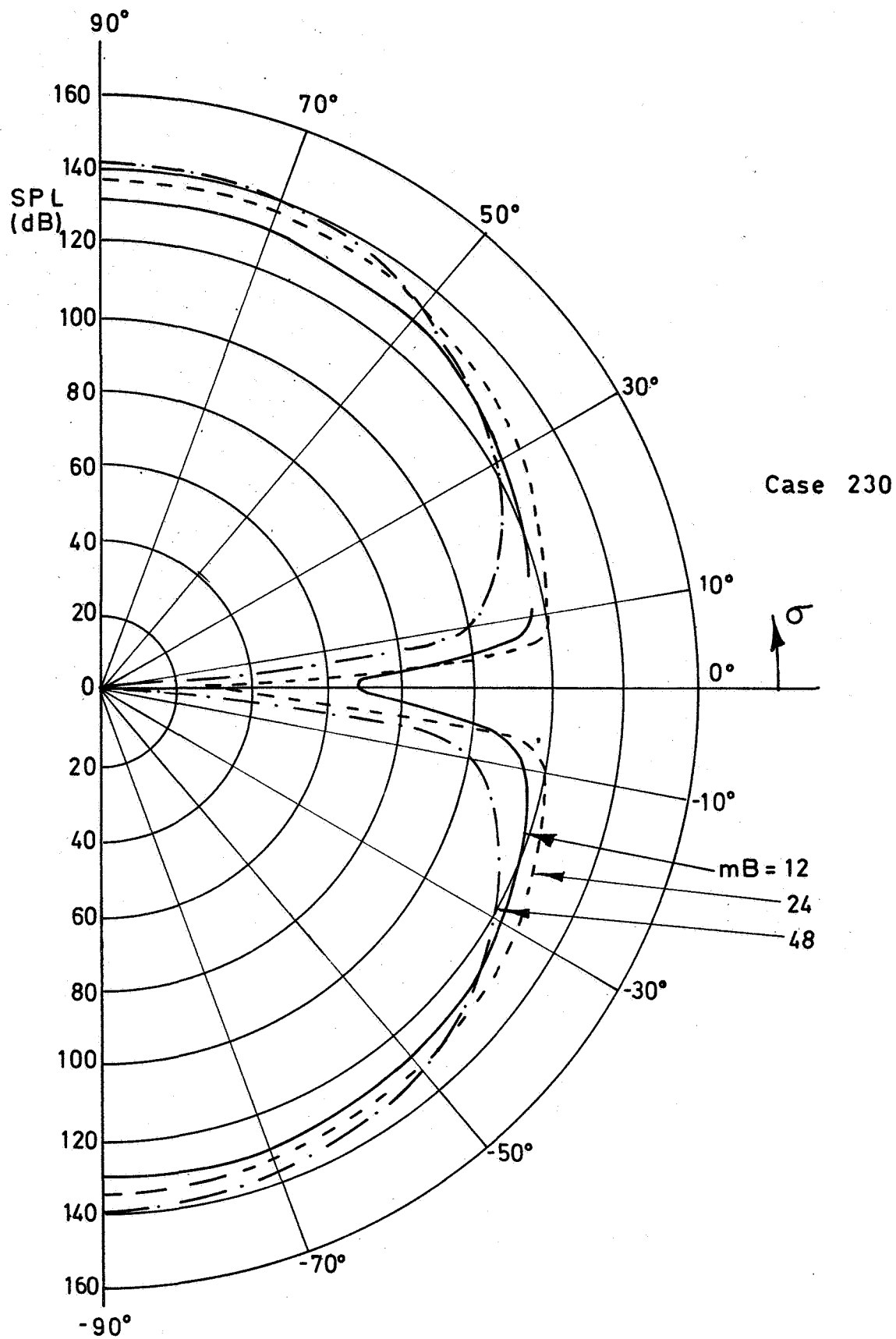


Fig. 2.3.20 Flat B.L. spectrum  $\beta = 24^\circ$  Polar elevation  $\vartheta = 0^\circ$

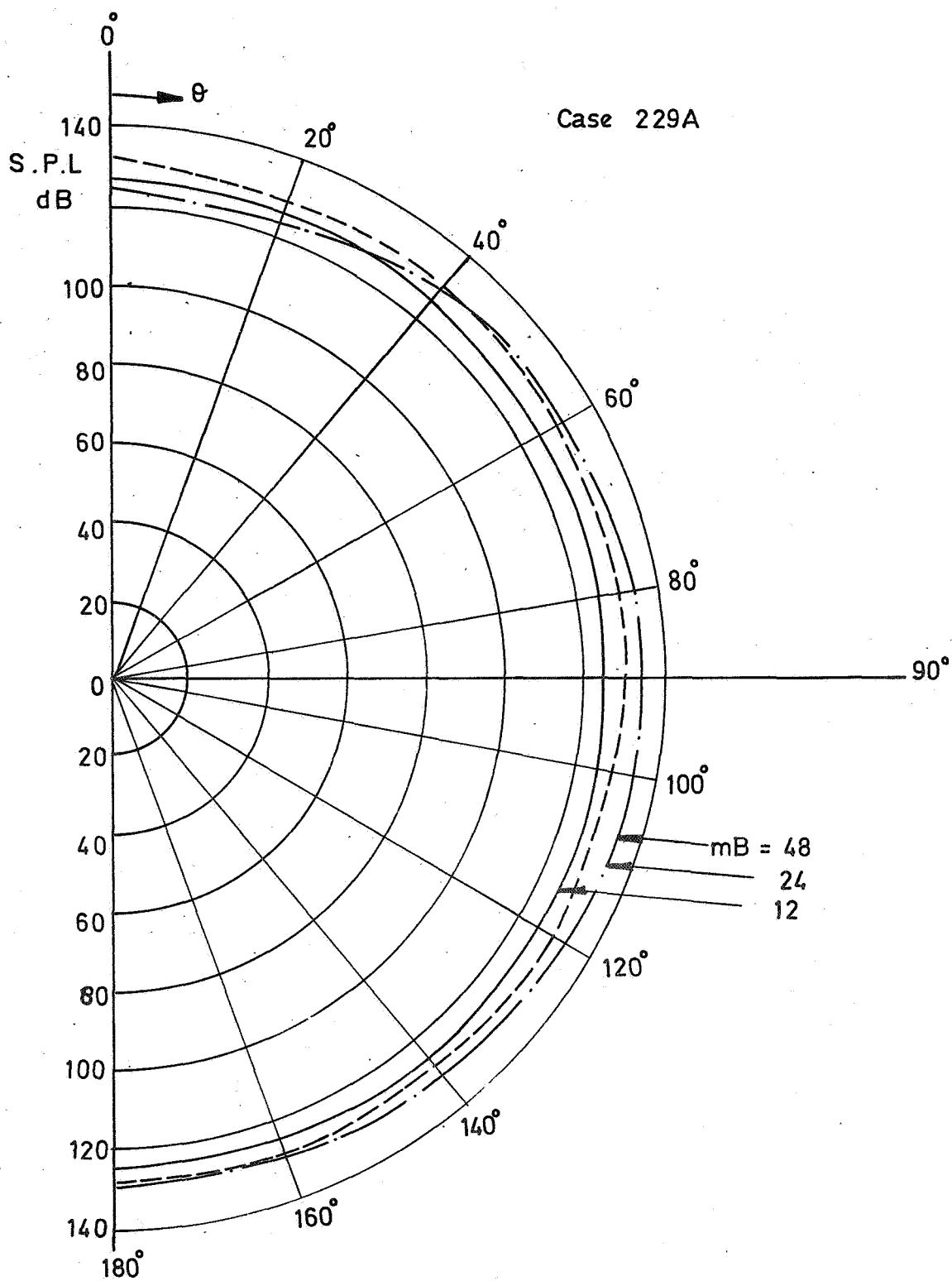


Fig. 2.3.21. Flat B.L spectrum  $\beta = 0^\circ$ . Polar plan  $\sigma = -30^\circ$

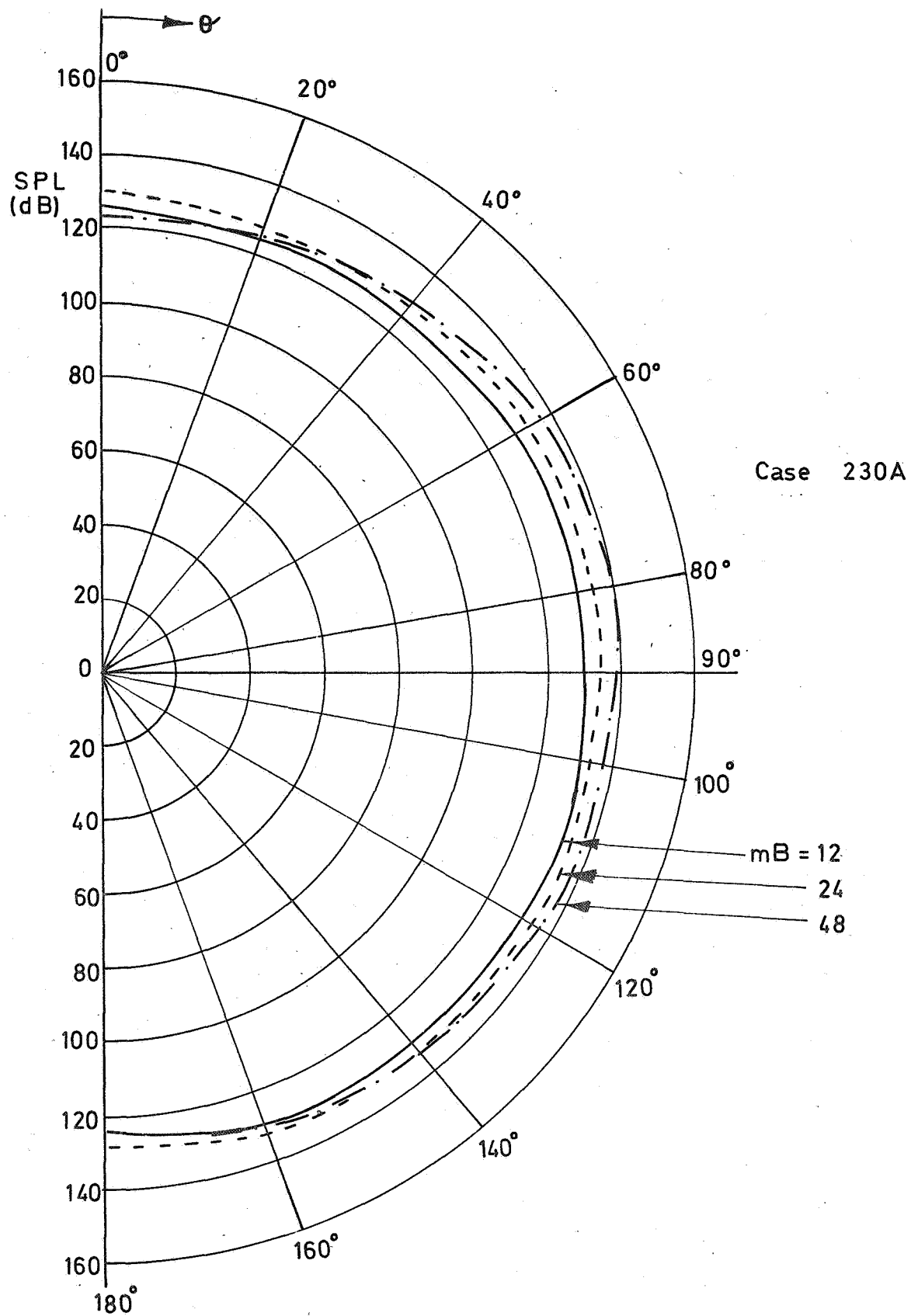


Fig. 2-3.22 Flat B.L. spectrum  $\beta = 24^\circ$  Polar plan  $\sigma = -30^\circ$

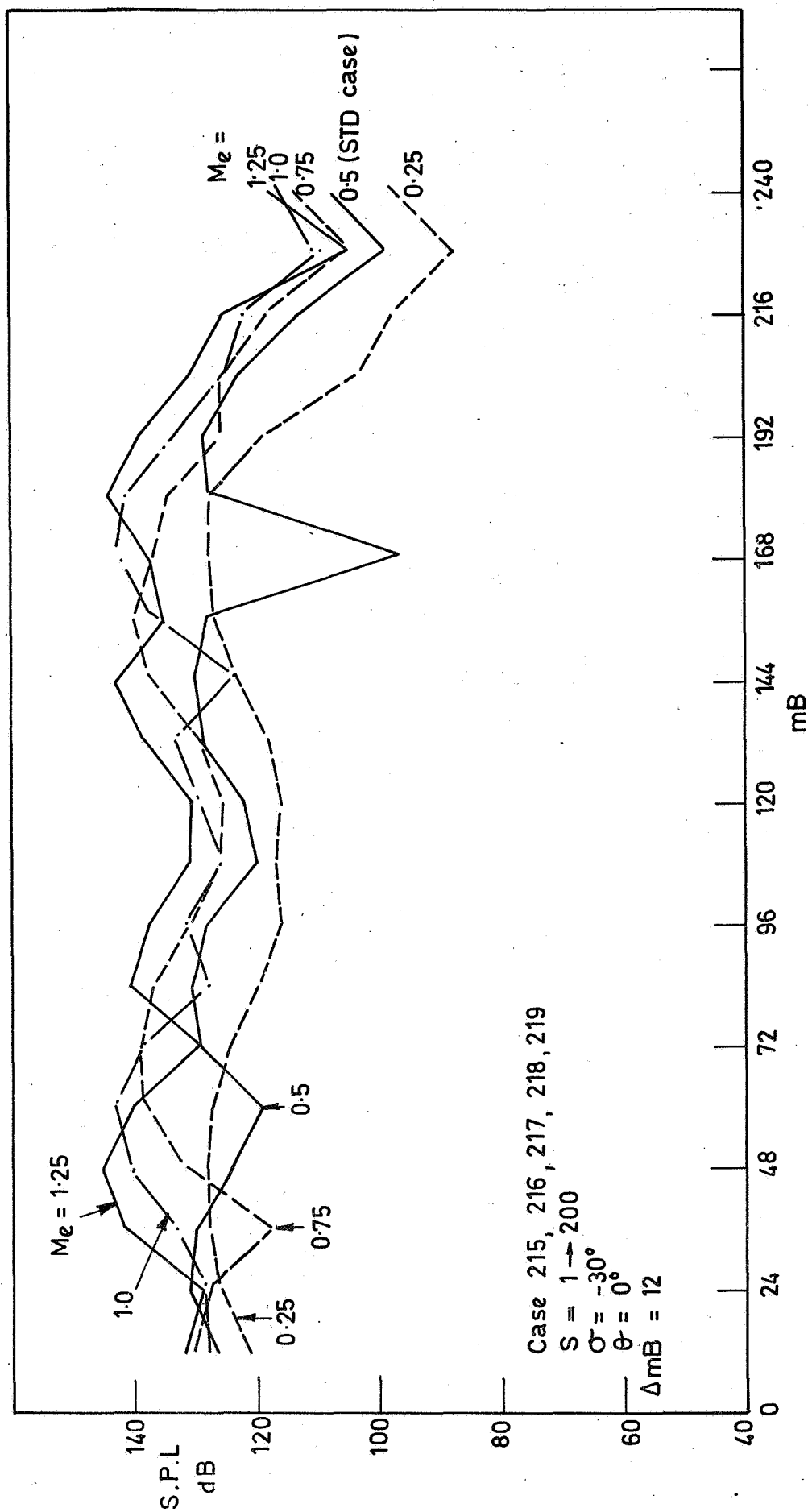


Fig 2.3.23 Flat B.L. spectrum Effect of Mach no. ( Low res. )

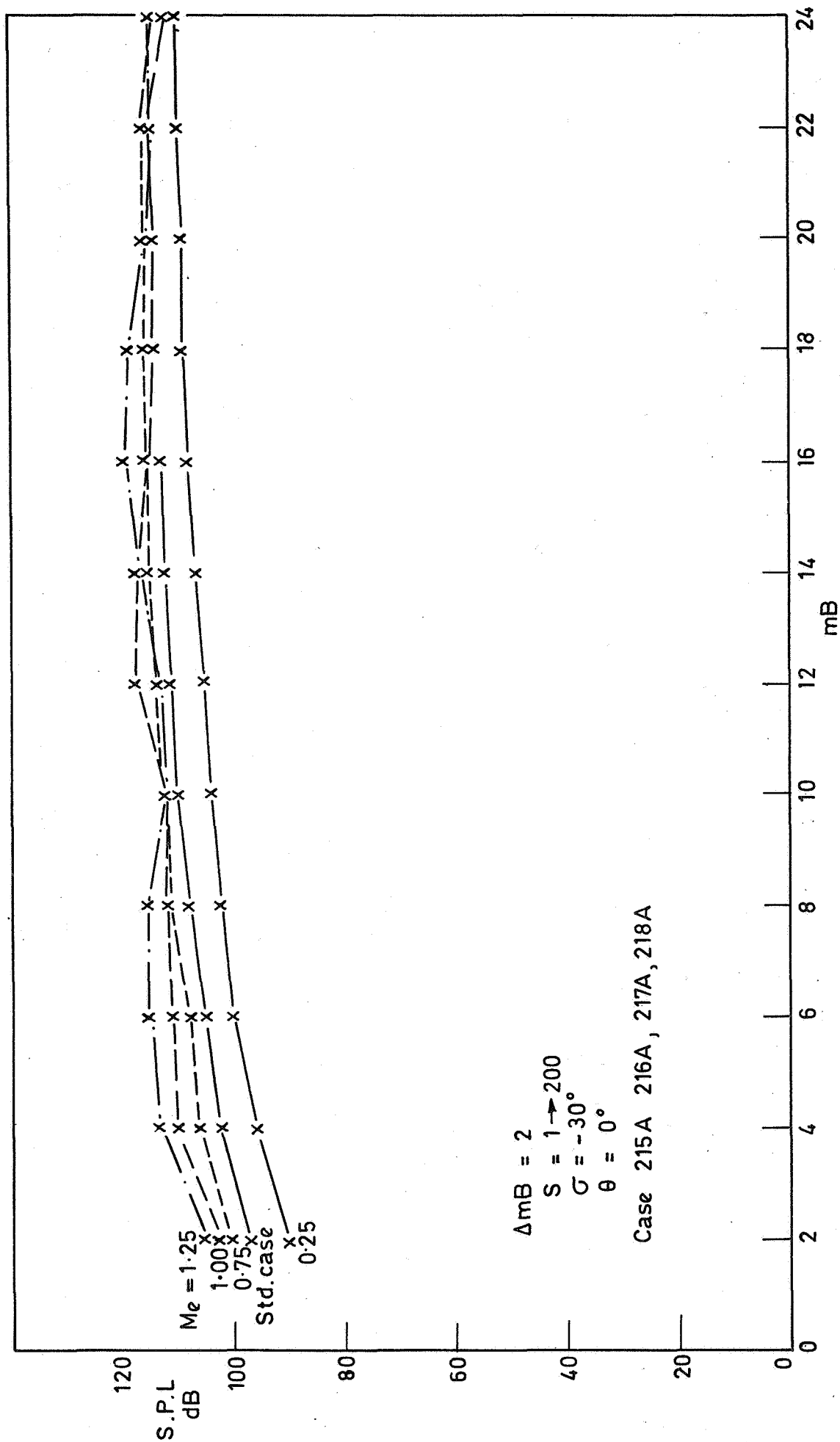


Fig. 2.3.24 Flat B.L. spectrum, effect of Mach no. (high res.)

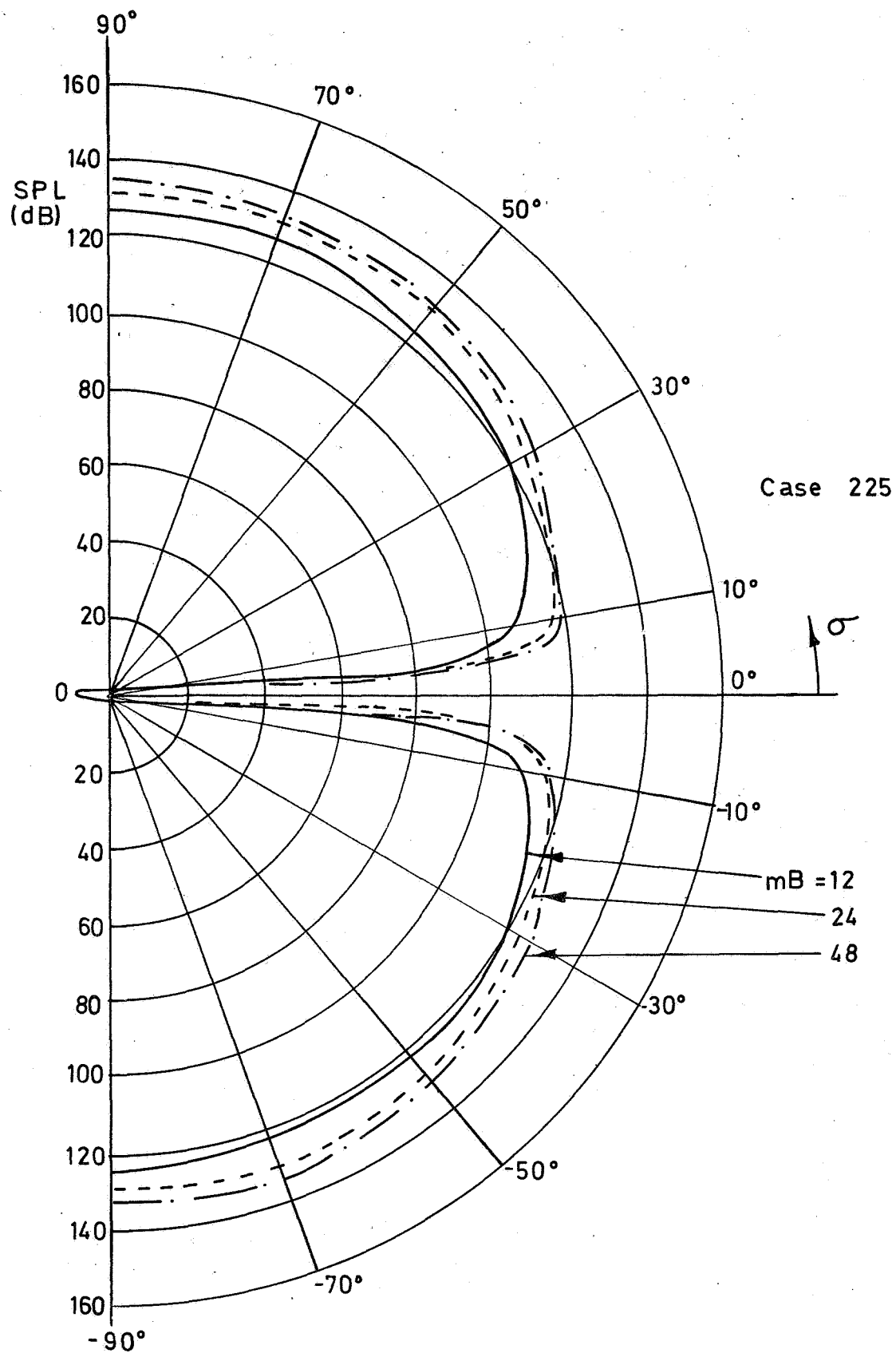


Fig. 2-3-25 Flat B.L. spectrum  $M_e=0.25$ . Polar elevation  $\theta=0^\circ$

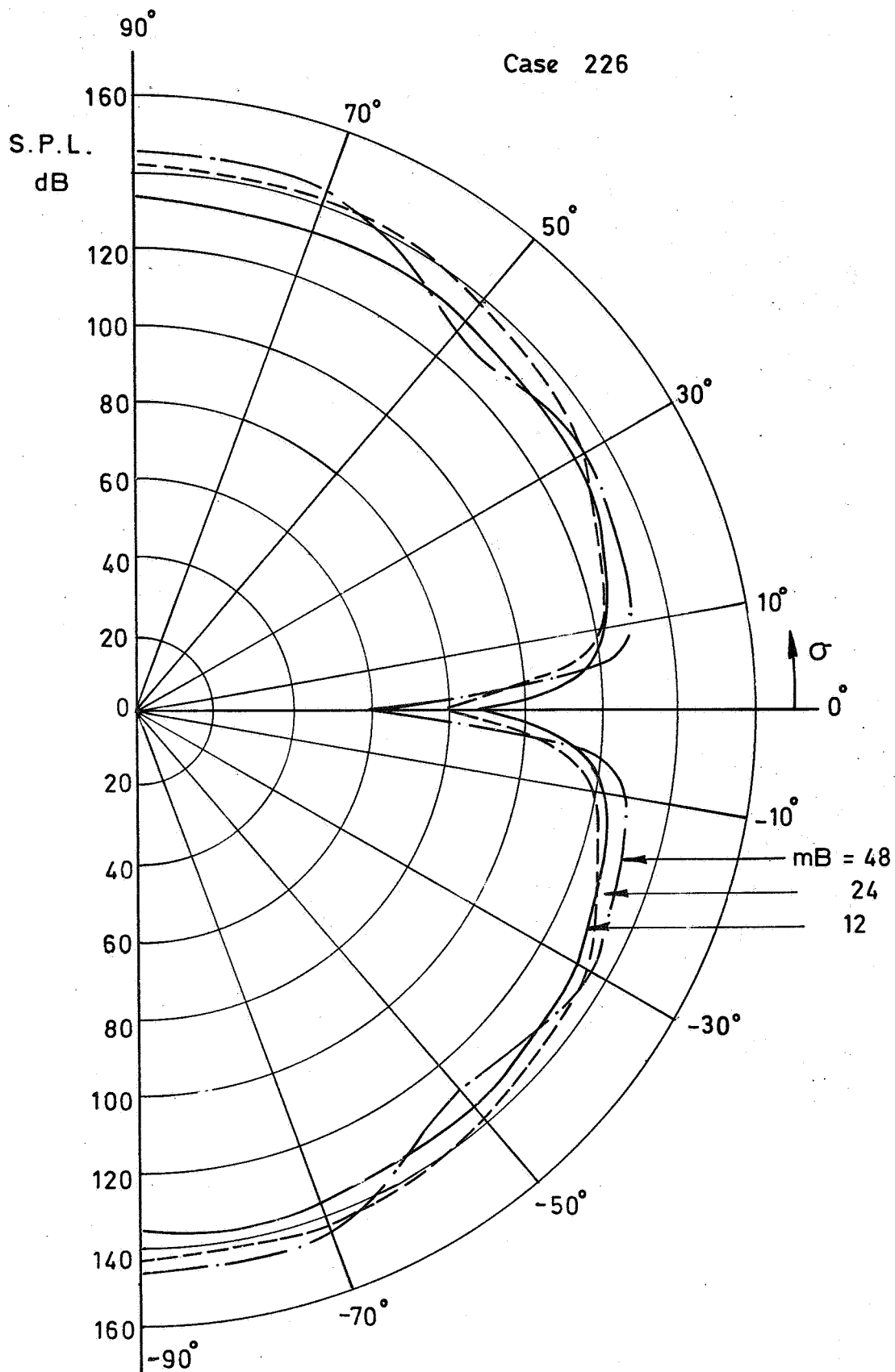


Fig. 2.3.26. Flat B.L spectrum .  $M_e = 0.75$  . Polar elevation  $\Theta = 0^\circ$

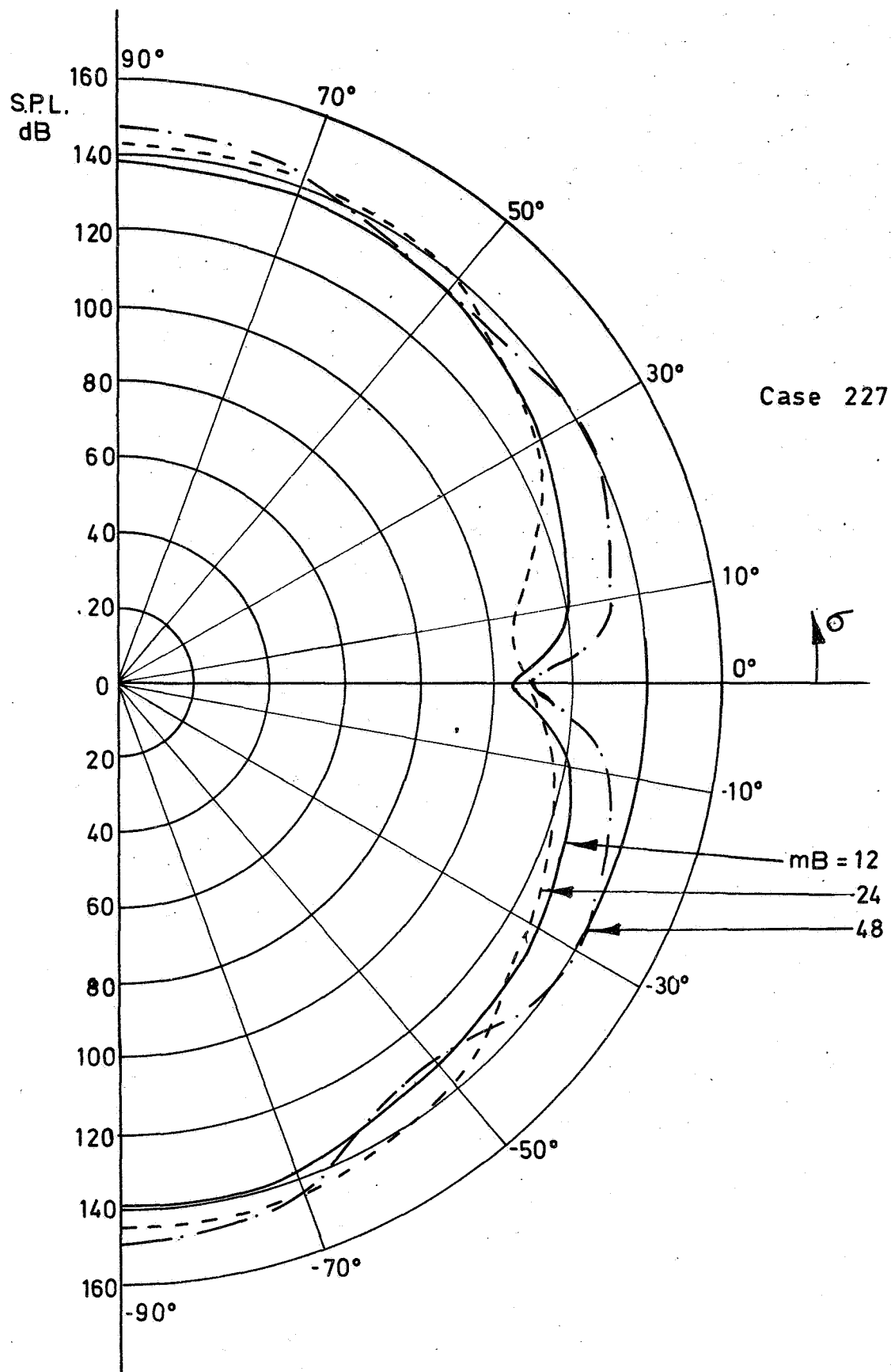


Fig. 2.3.27 Flat B.L. spectrum  $M_e = 1.0$   
Polar elevation  $\theta = 0^\circ$

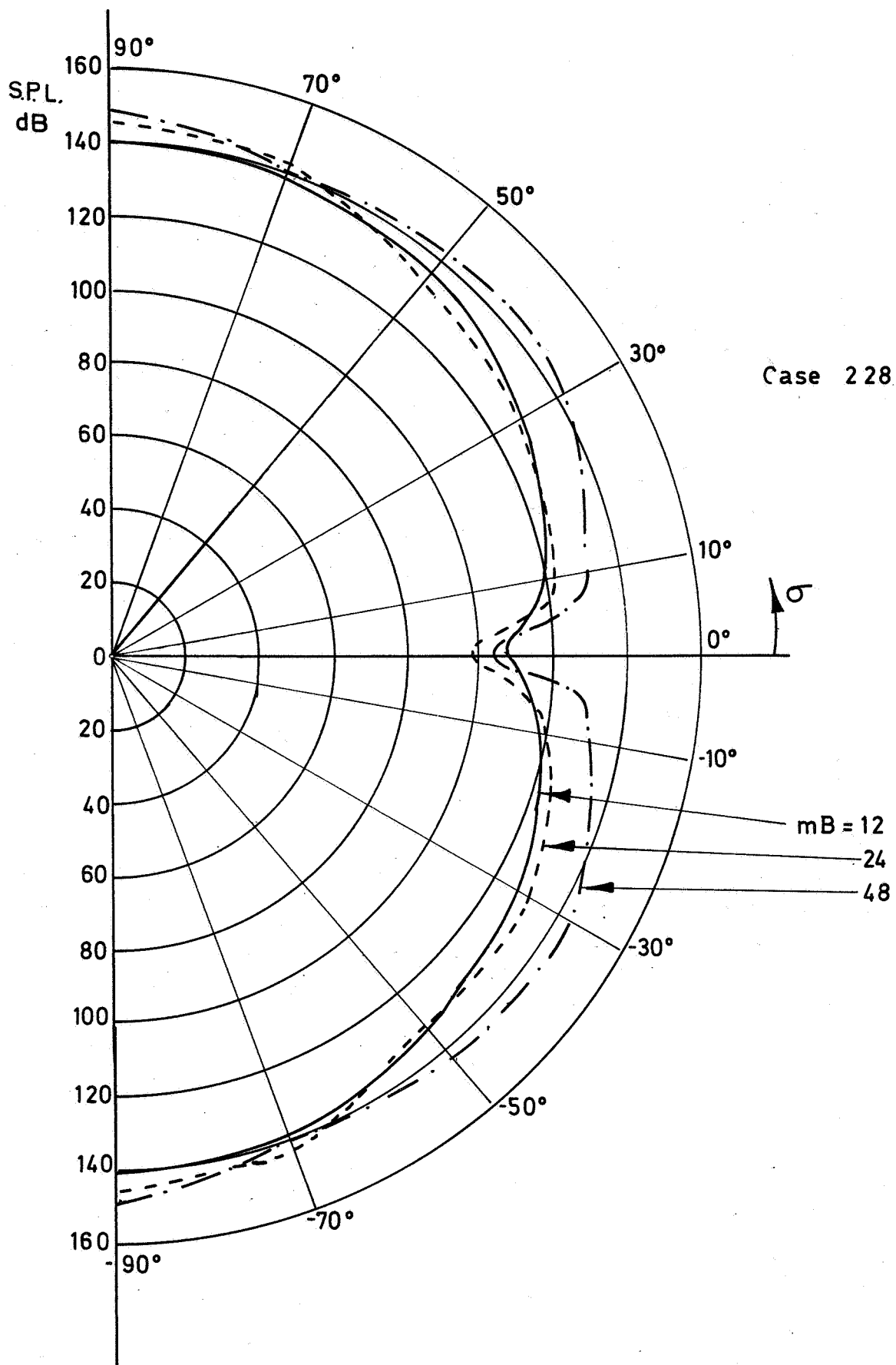


Fig. 2.3.28 Flat B.L. spectrum  $M_e = 1.25$   
Polar elevation  $\sigma = 0^\circ$

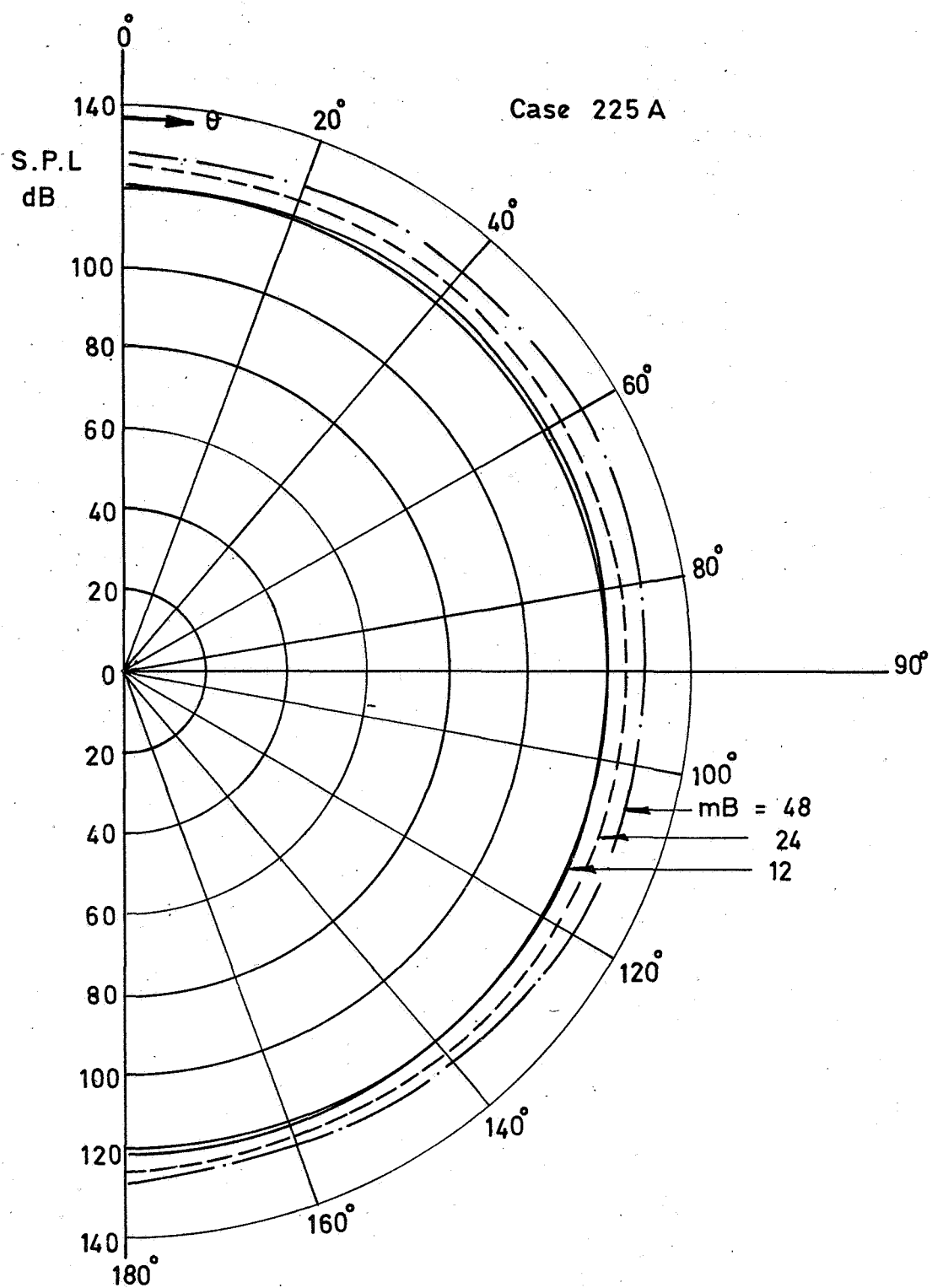


Fig. 2.3.29. Flat B.L. spectrum  $M_e = 0.25$ . Polar plan.  $\sigma = -30^\circ$

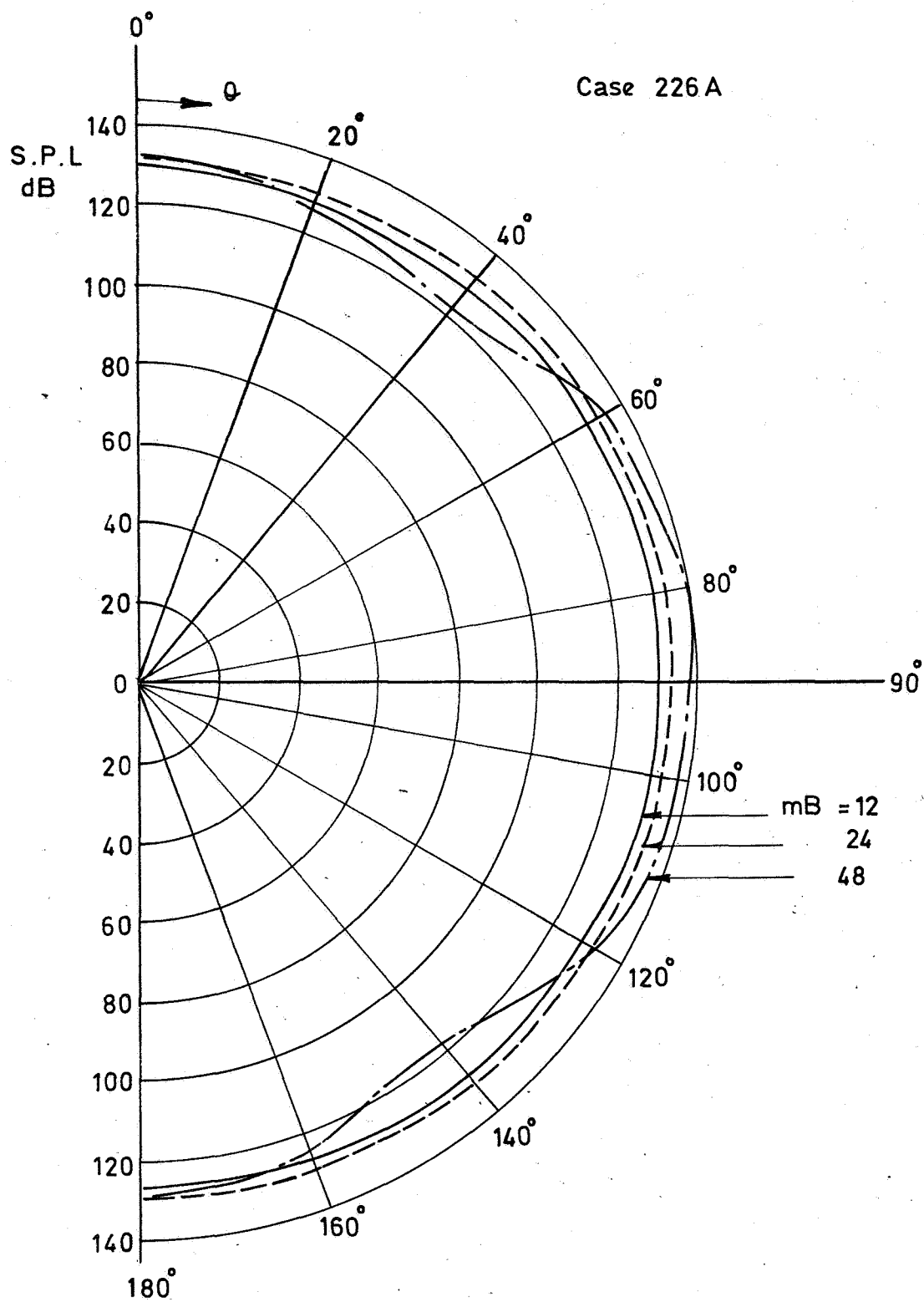


Fig. 2.3.30. Flat B.L spectrum  $M_e = 0.75$  . Polar plan  $\sigma = -30^\circ$

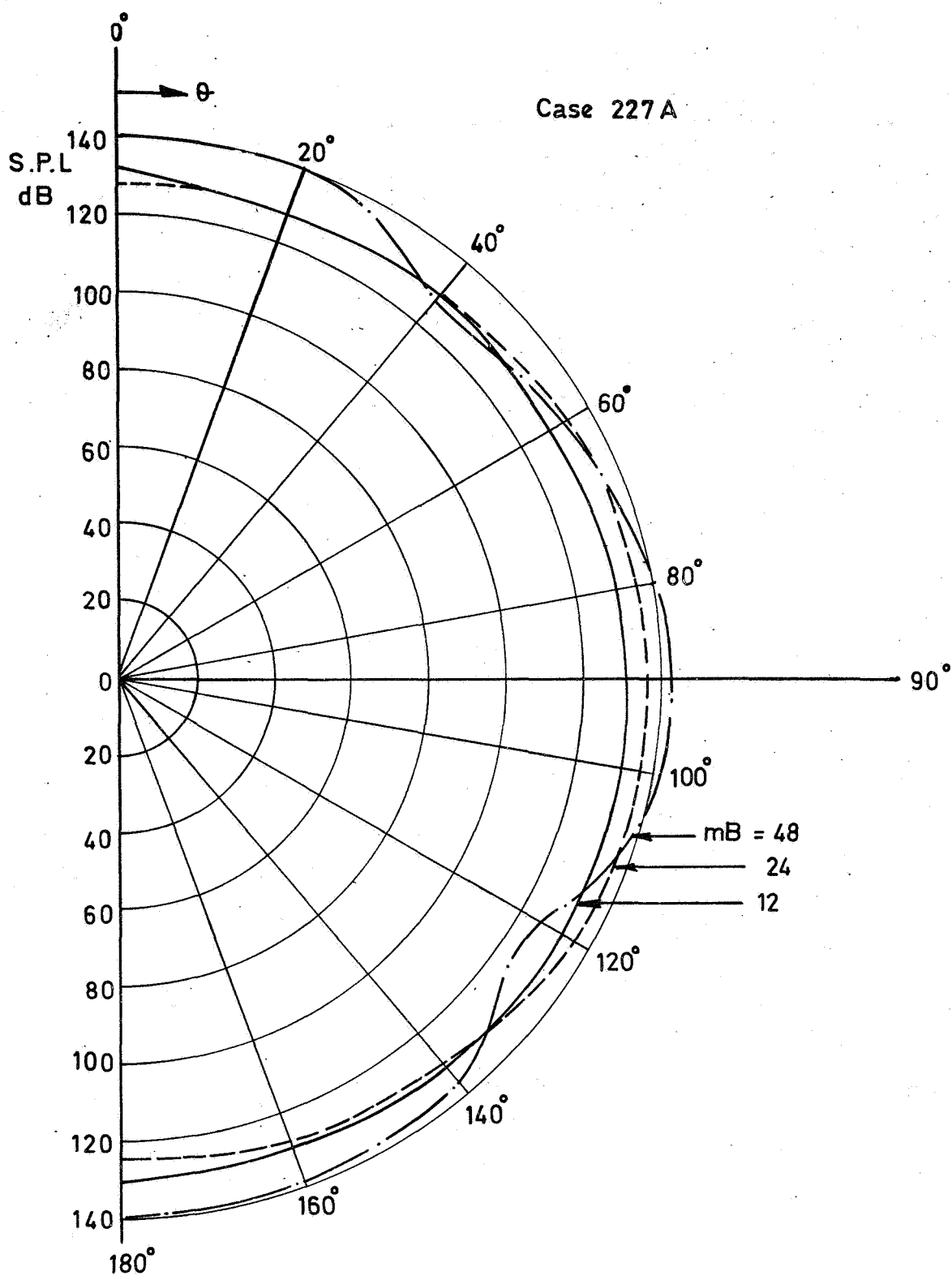


Fig. 2.3.31 . Flat B.L spectrum .  $M_e = 1.0$  . Polar plan  $\sigma = -30^\circ$

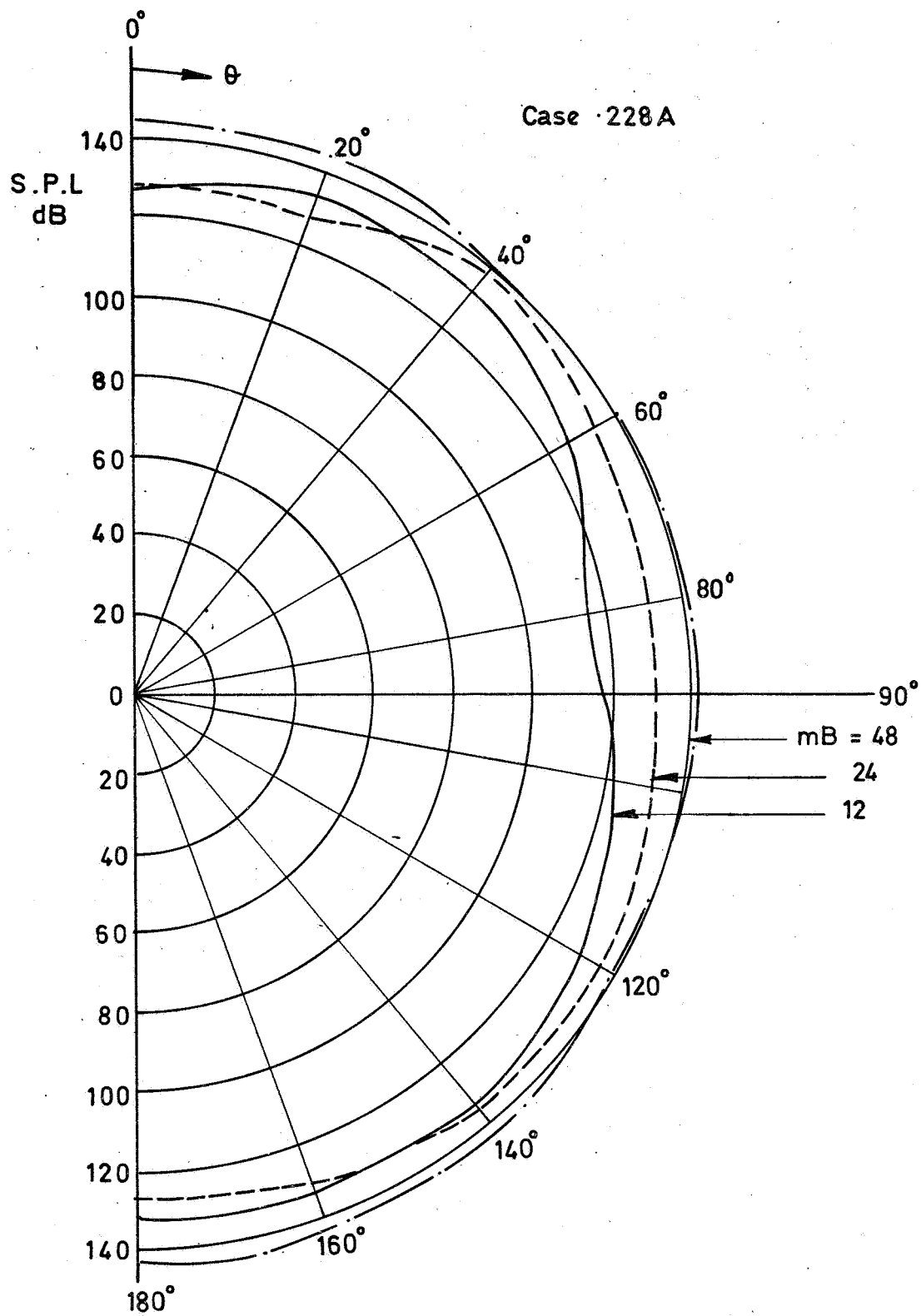


Fig. 2.3.32 Flat B.L. spectrum .  $M_e = 1.25$ . Polar plan  $\sigma = -30^\circ$

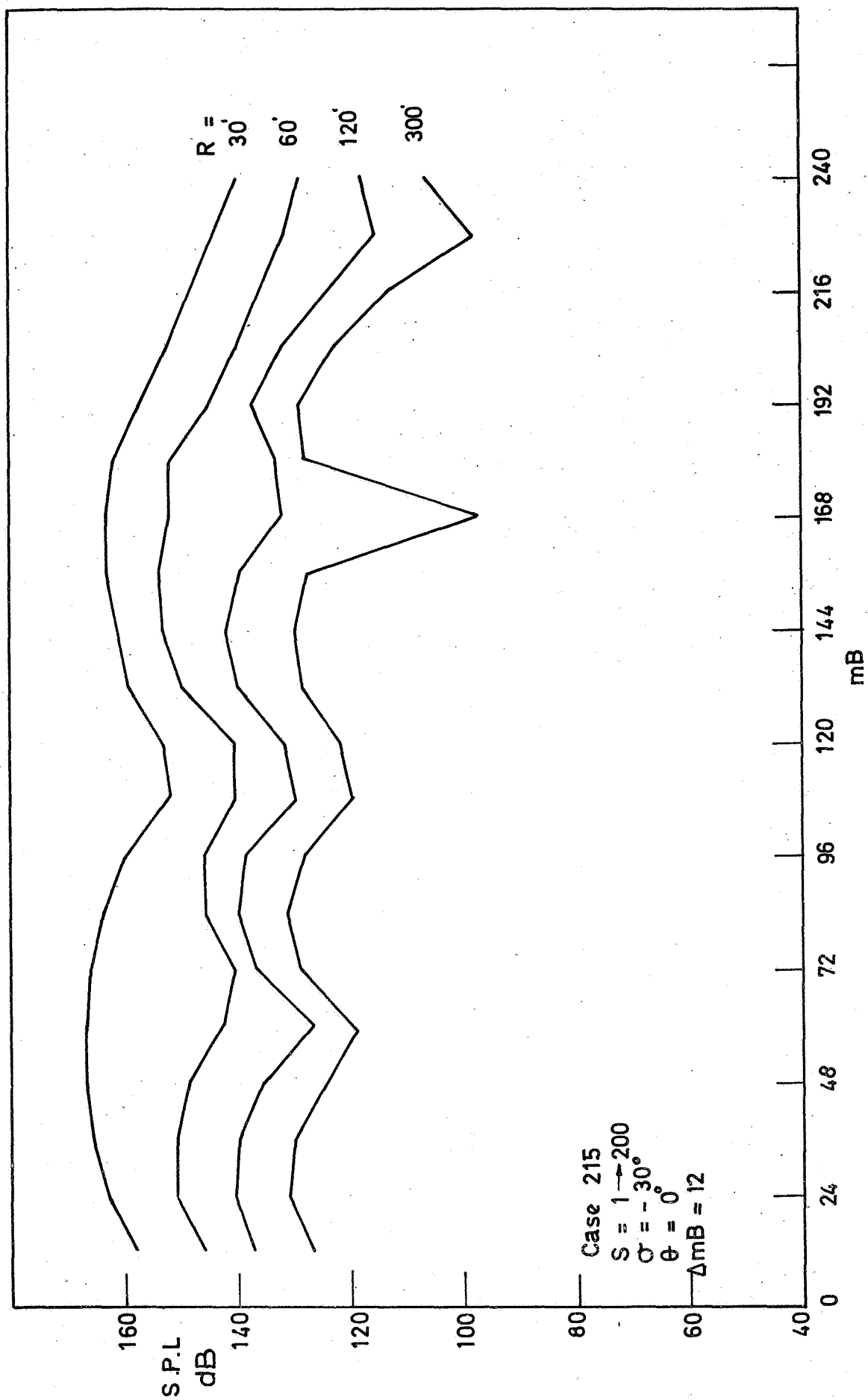


Fig 2.3.33 Flat B.L. spectrum . Effect of observer distance . (Low res.)

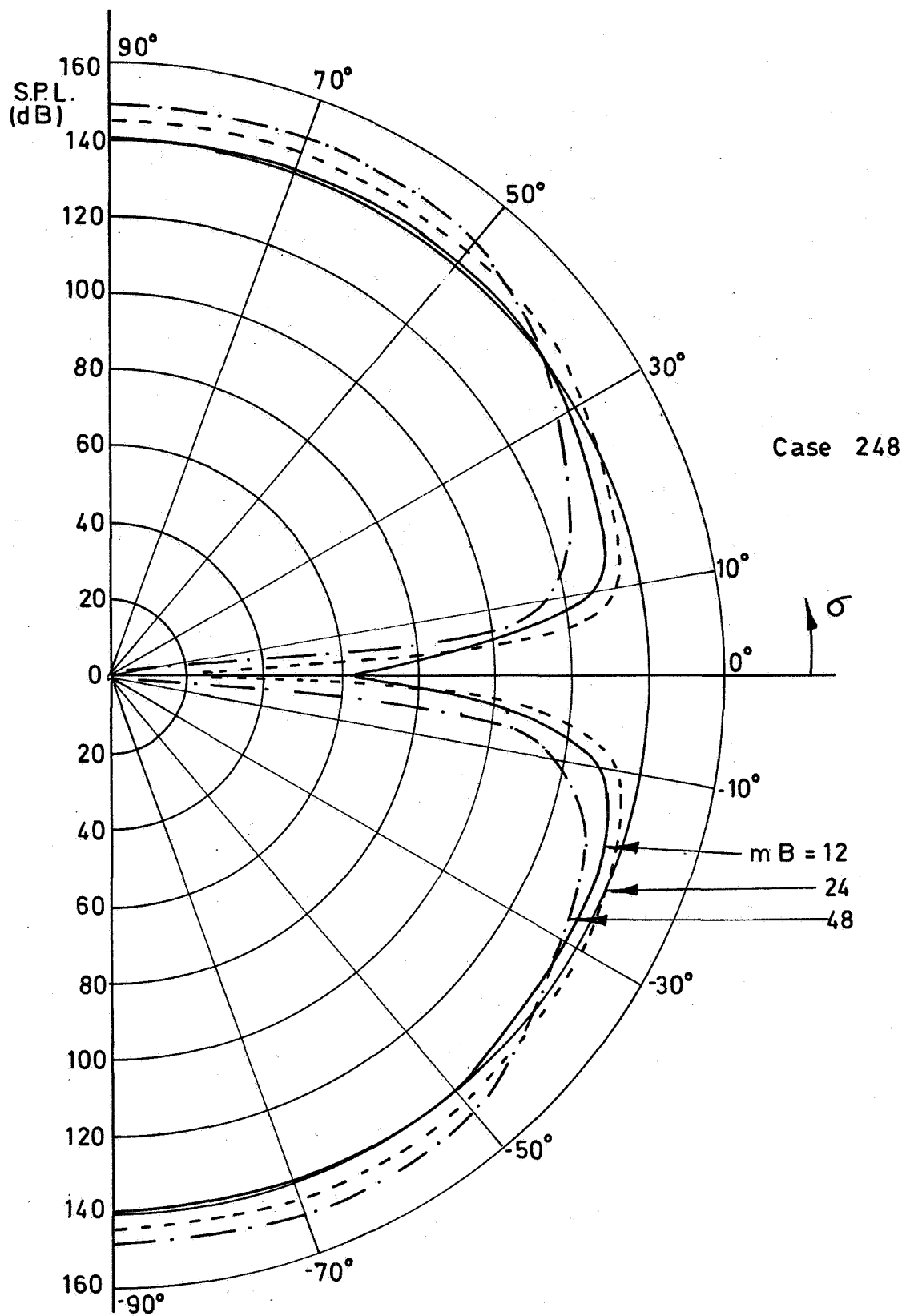


Fig. 2.3.34 Flat B.L. spectrum  $R=120'$   
Polar elevation  $\sigma=0^\circ$

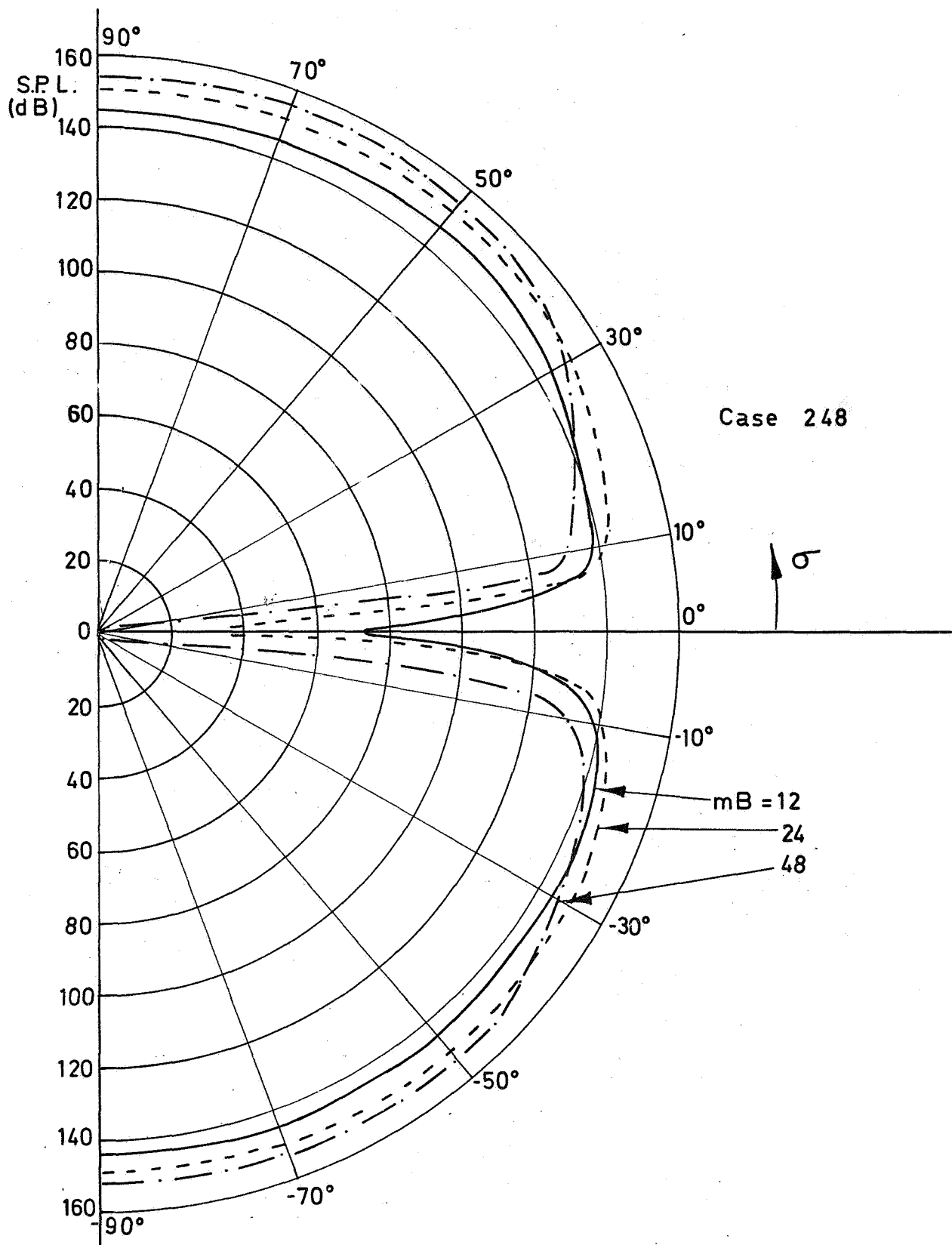


Fig. 2.3.35 Flat B.L. spectrum  $R = 60'$   
Polar elevation  $\theta = 0^\circ$

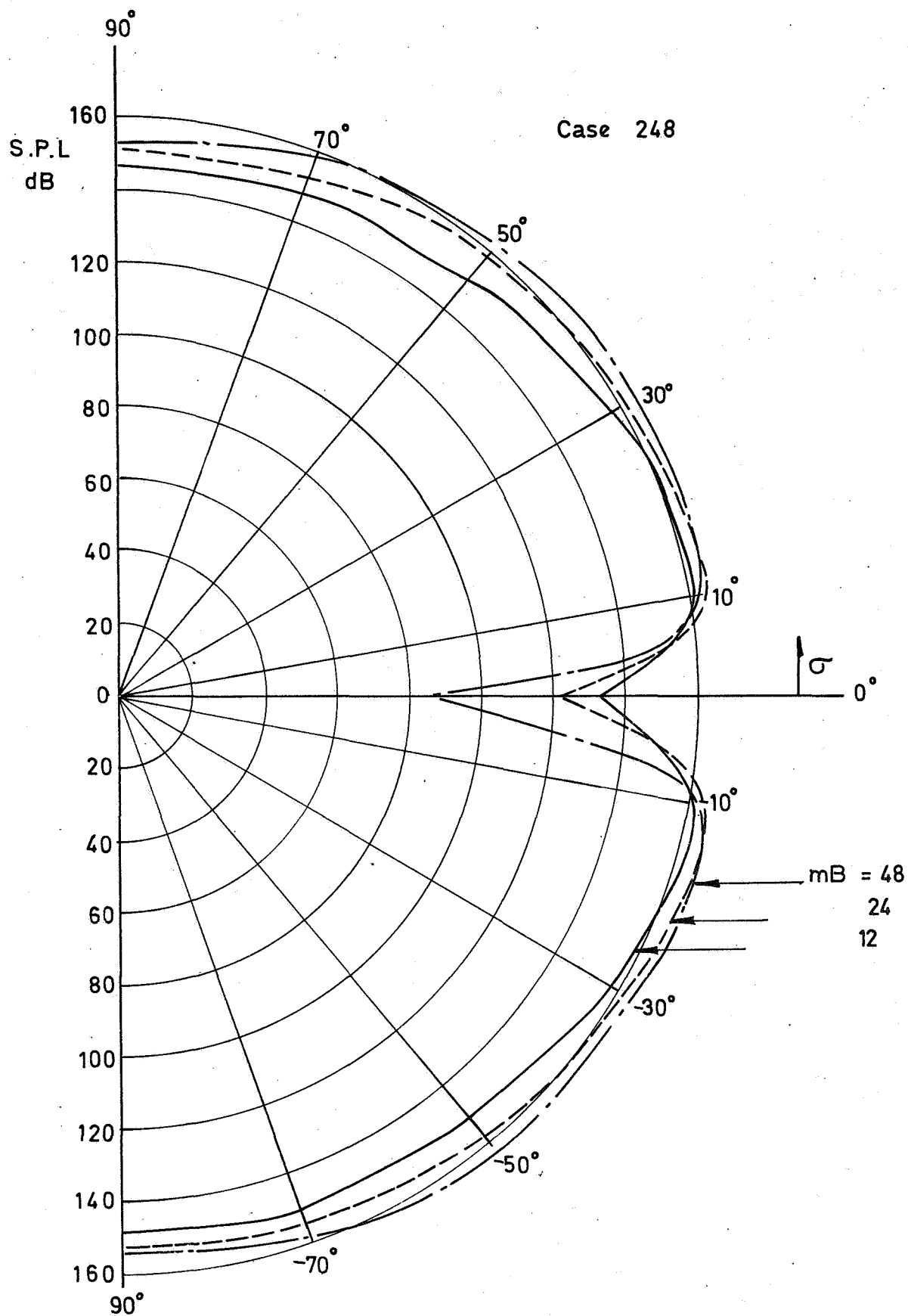


Fig. 2.3.36. B.L. spectrum .  $R = 30'$  . Polar elevation  $\Theta = 0^\circ$

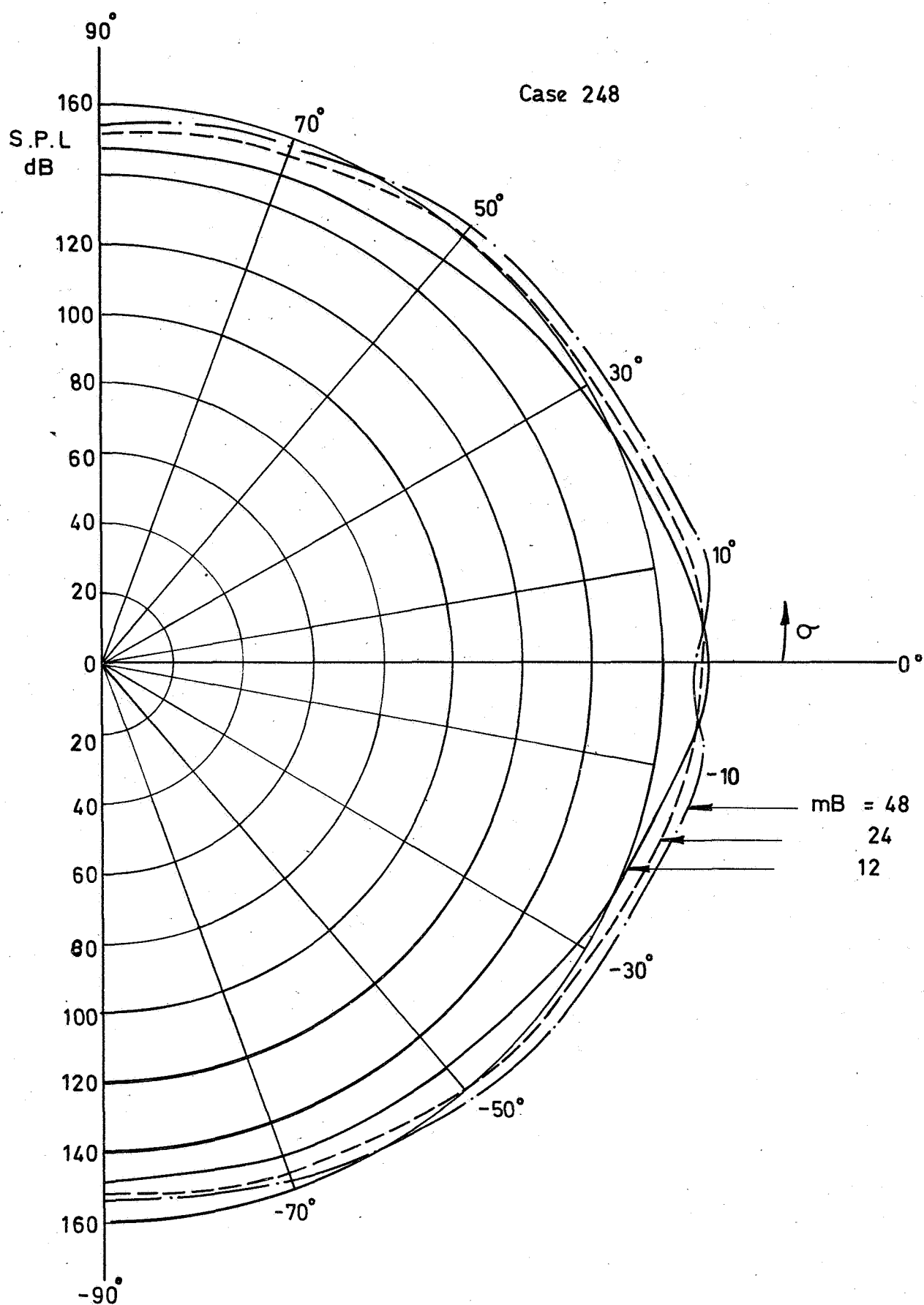


Fig. 2.3.37. Flat B.L. spectrum .  $R = 26'$  . Polar elevation  $\Theta = 0^\circ$

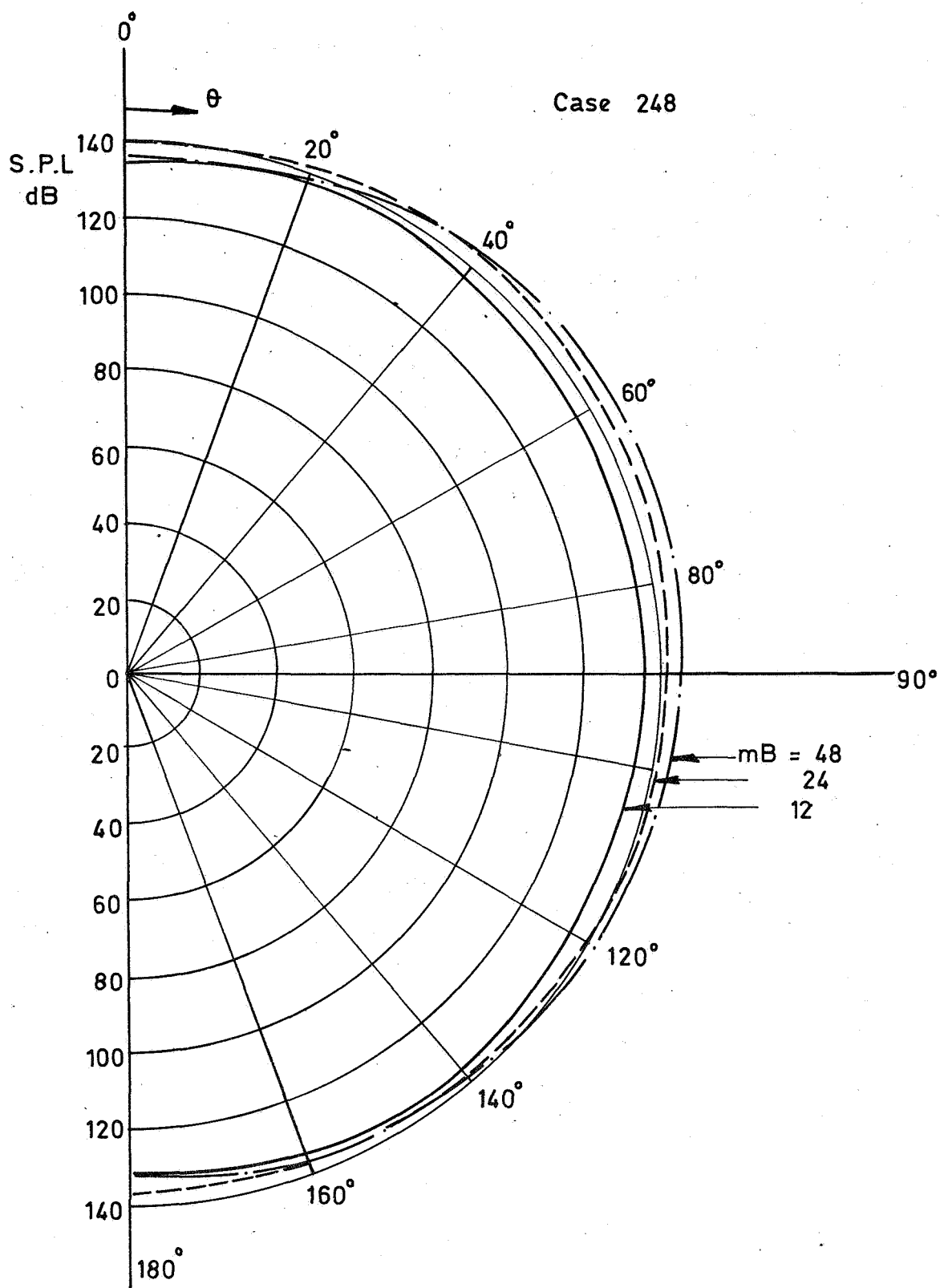


Fig. 2.3.38 Flat B.L spectrum,  $R = 120^\circ$ , Polar plan,  $\sigma = -30^\circ$

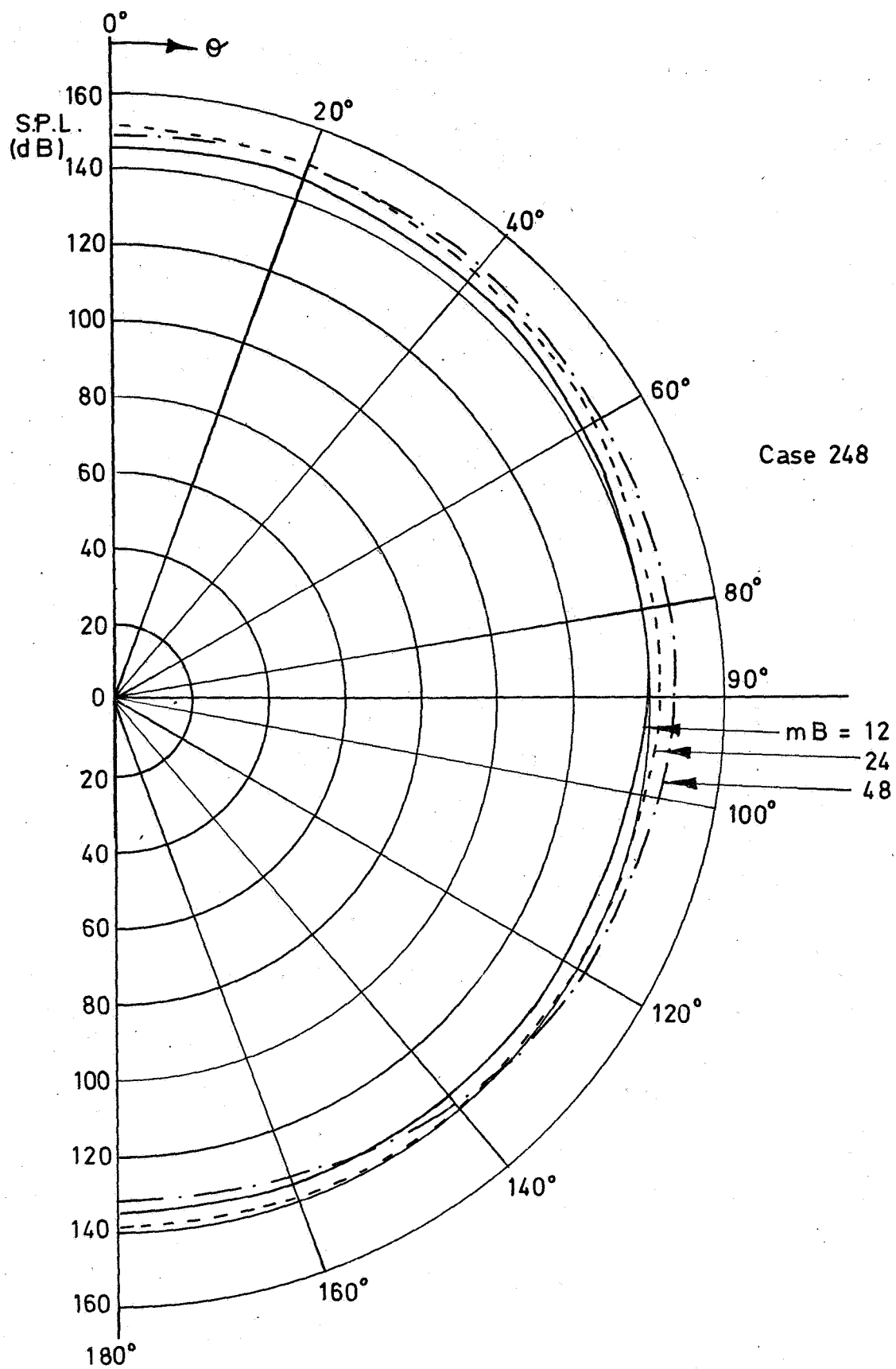


Fig. 2.3.39 Flat B.L. spectrum  $R = 60'$   
Polar plan  $\sigma = -30^\circ$

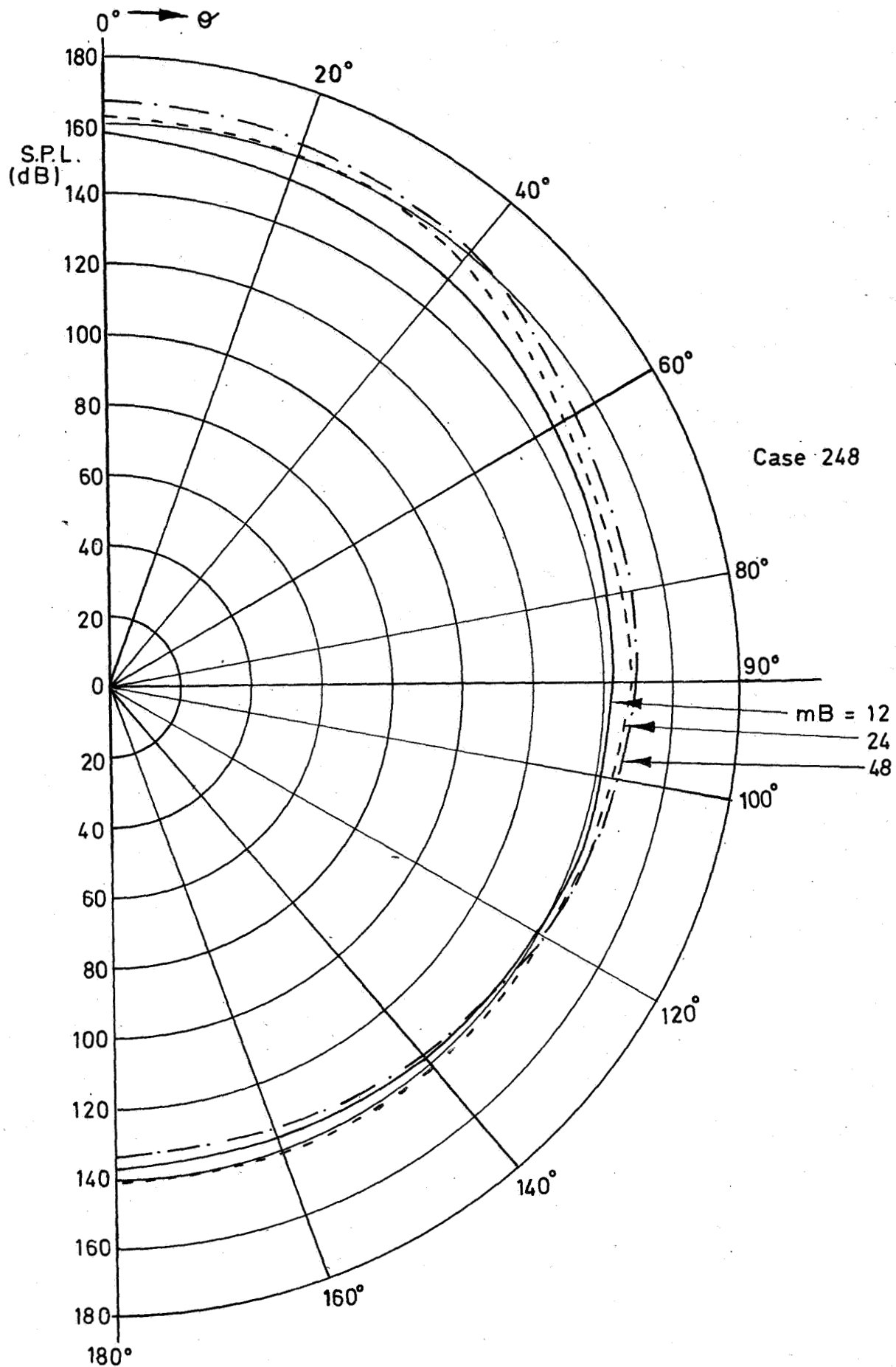


Fig. 2.3.40 Flat B L spectrum  $R = 30'$   
Polar plan  $\sigma = -30^\circ$

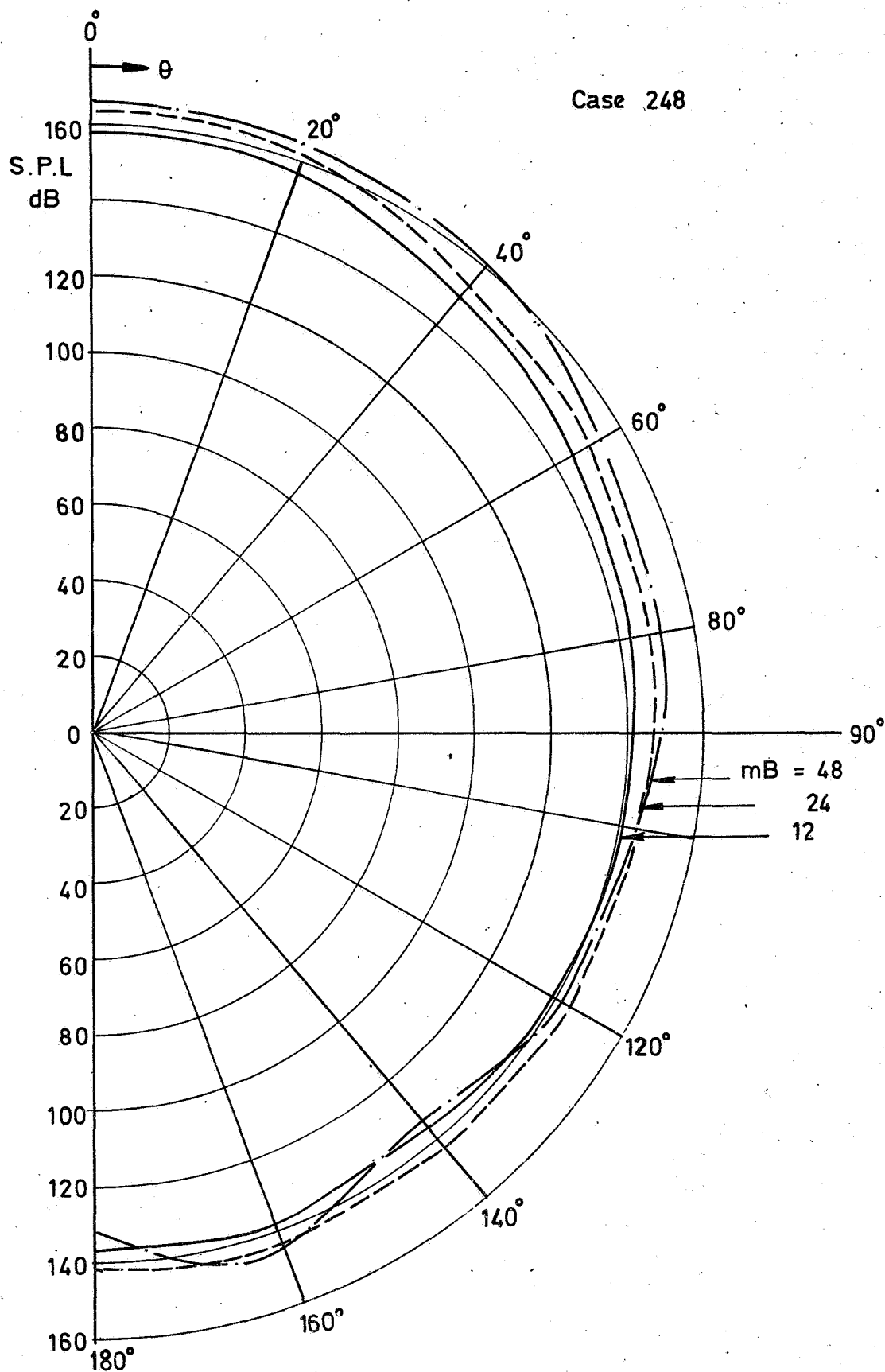


Fig. 2.3.41. Flat B.L spectrum .  $R = 26'$  . Polar plan .  $\sigma = -30^\circ$

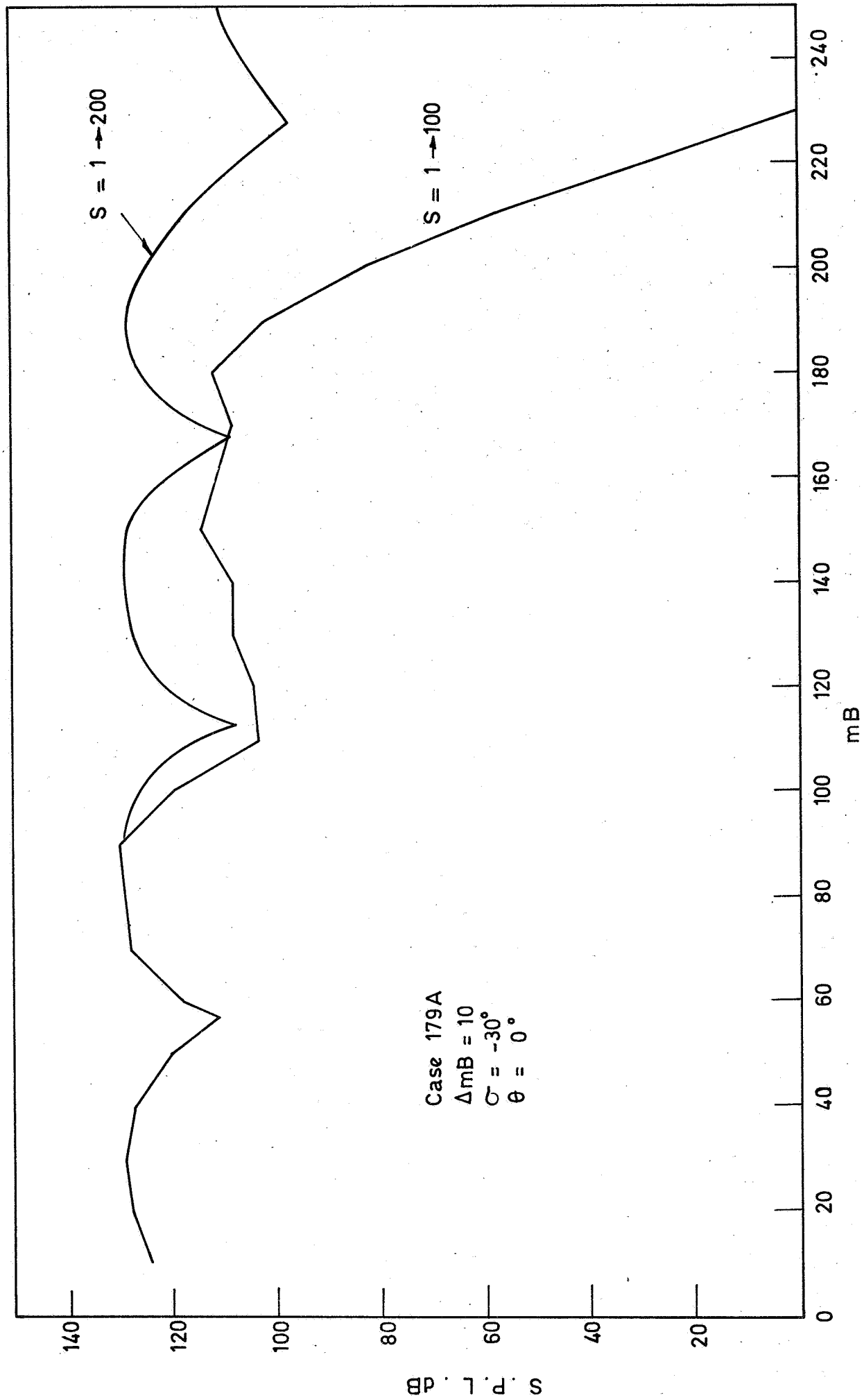


Fig 2.3.42 Flat B.L. spectrum Effect of number of B.L. harmonics

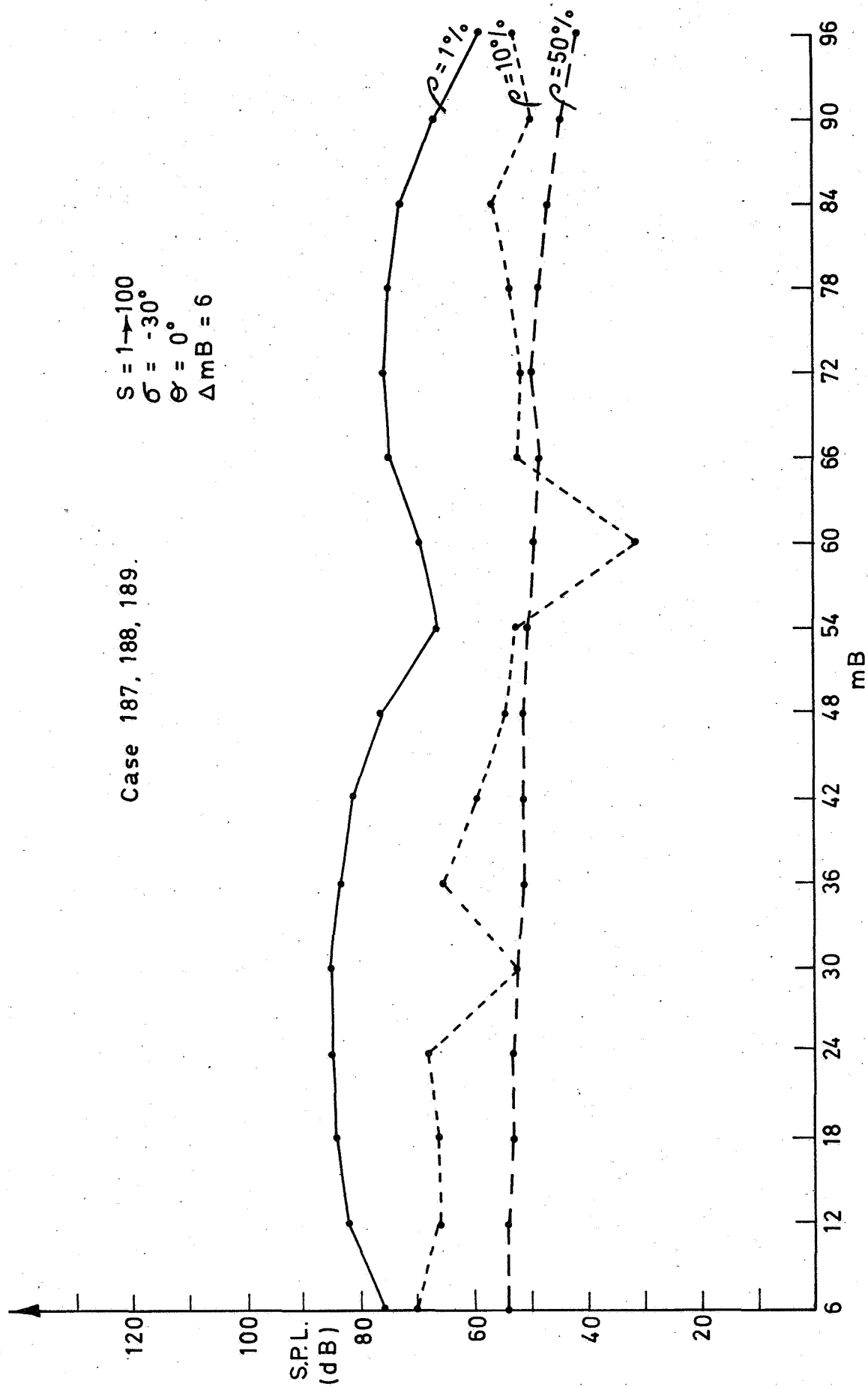


Fig. 2.4.1  
 B.L. Azimuth functions, effect of load solidity ( $\rho$ ) Low res.

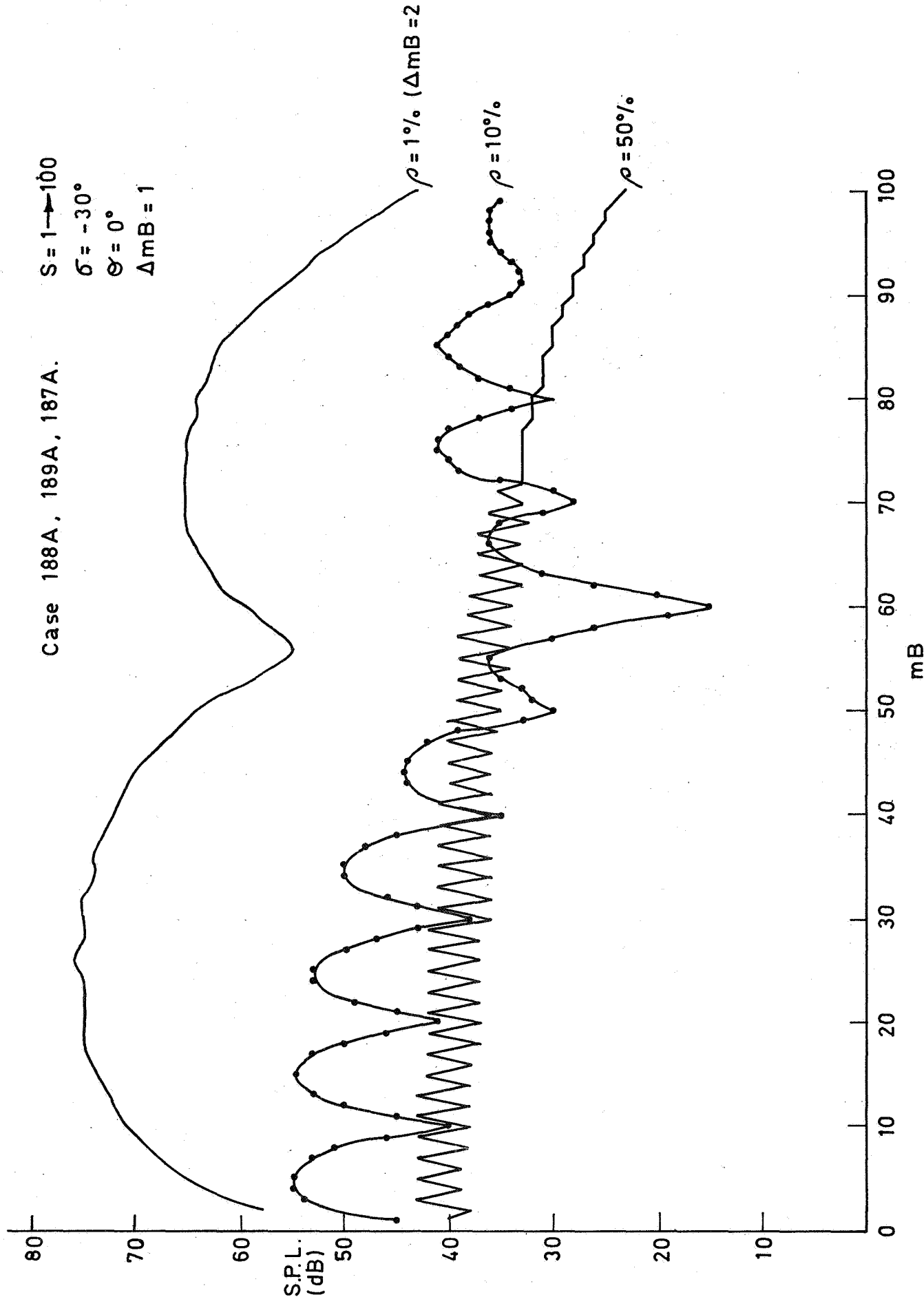


Fig.2.4.2 B.L.Azimuth functions, effect of load solidity ( $\rho$ ) High res.

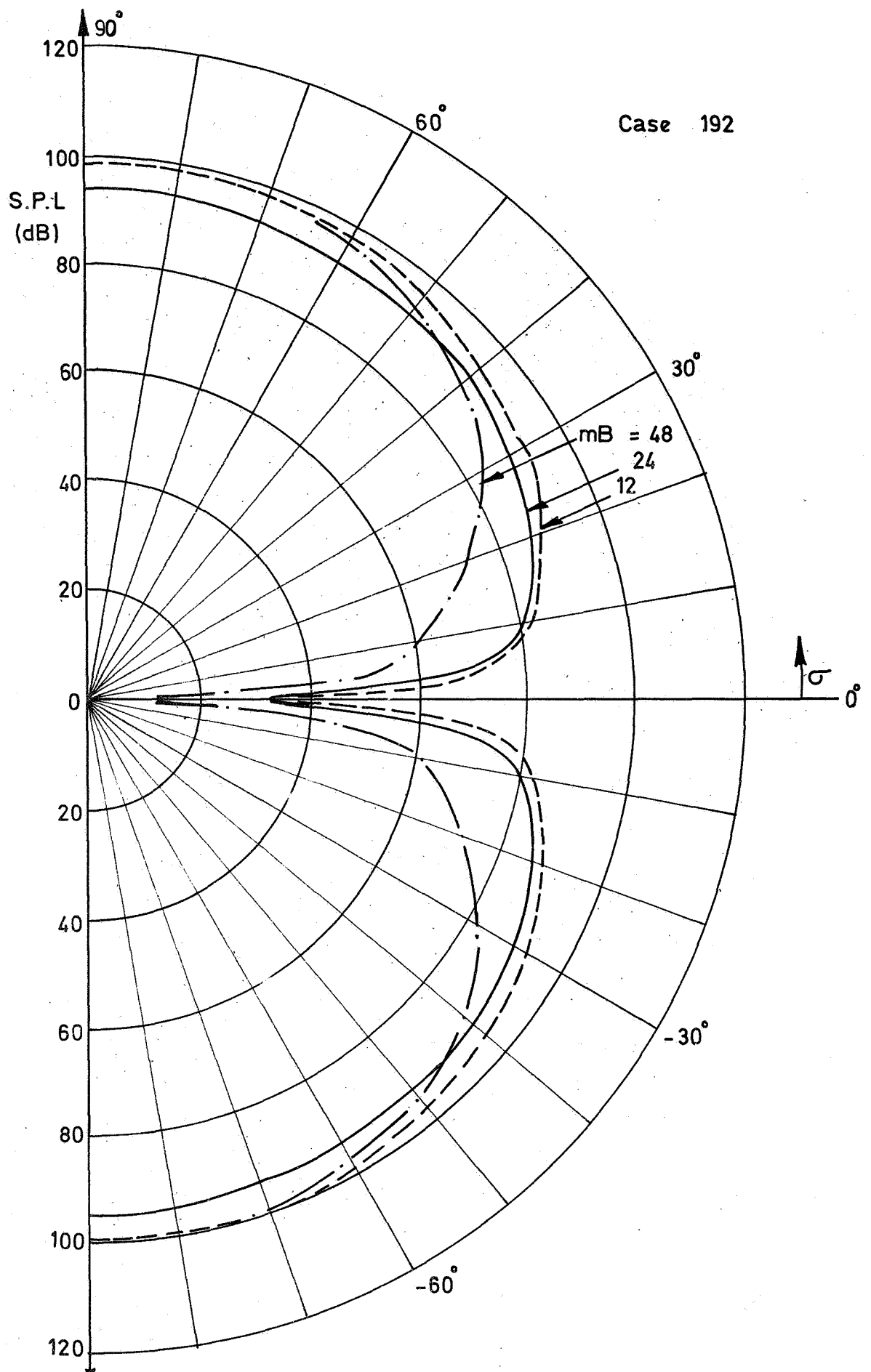


Fig 2.4-3 Azimuth functions -  $\ell = 1\%$   
polar elevation  $\theta = 0^\circ$

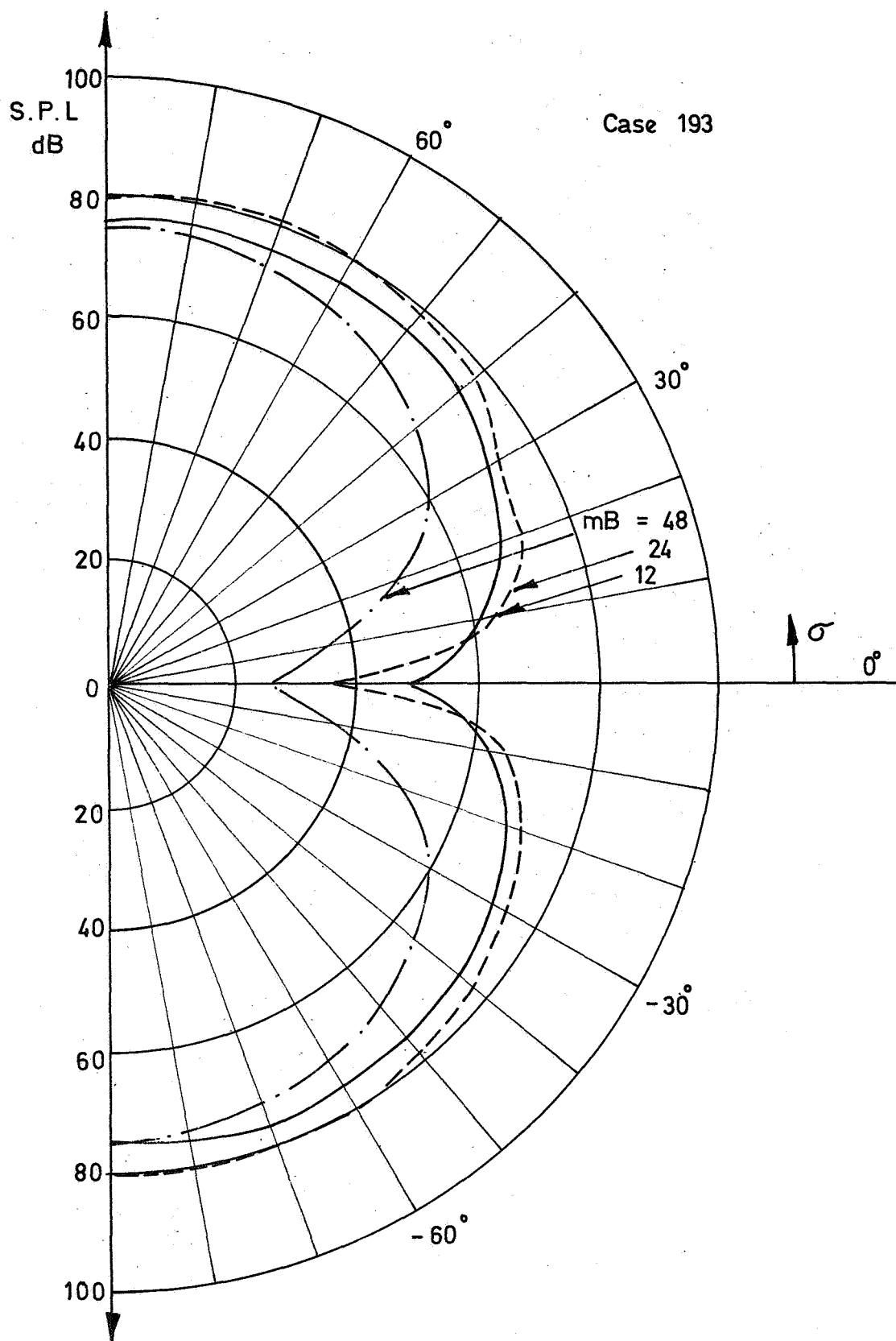


Fig. 2-4-4 Azimuth functions -  $\rho = 10\%$   
polar elevation  $\theta = 0^\circ$

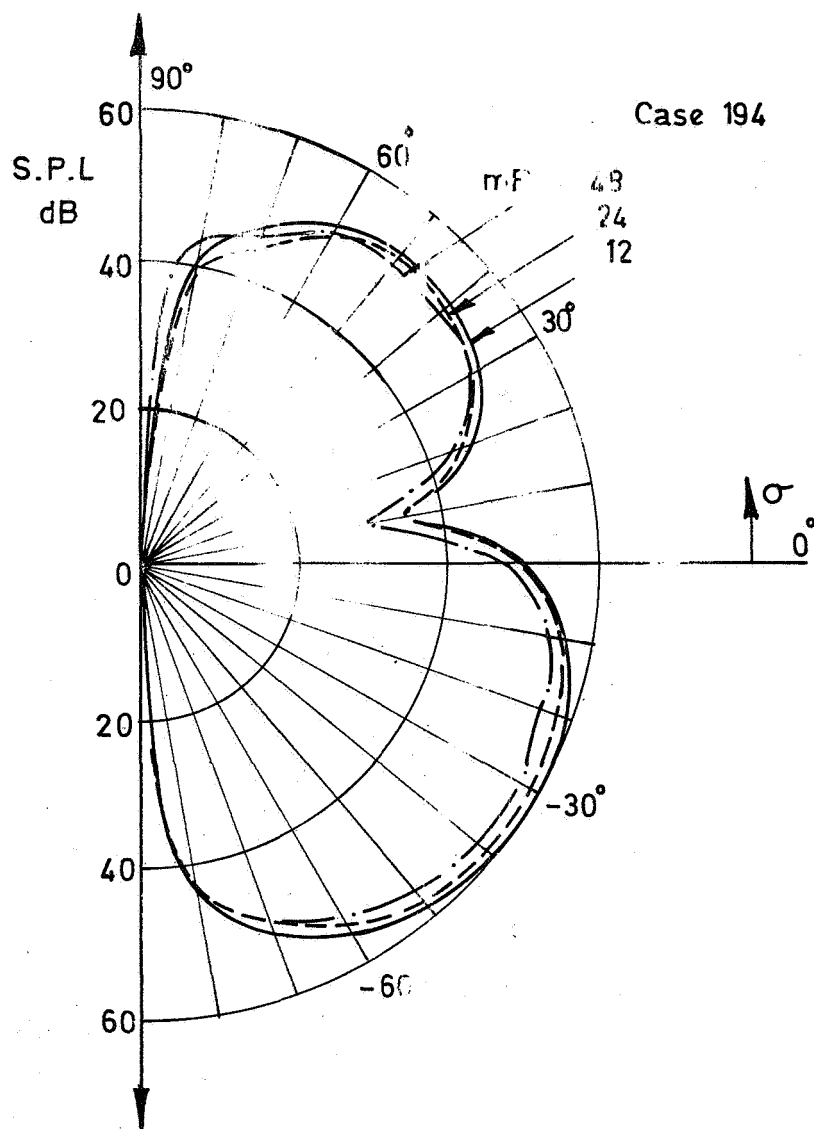


Fig 2.4.5 Azimuth functions -  $\rho = 50\%$   
polar elevation  $\theta = 0^\circ$

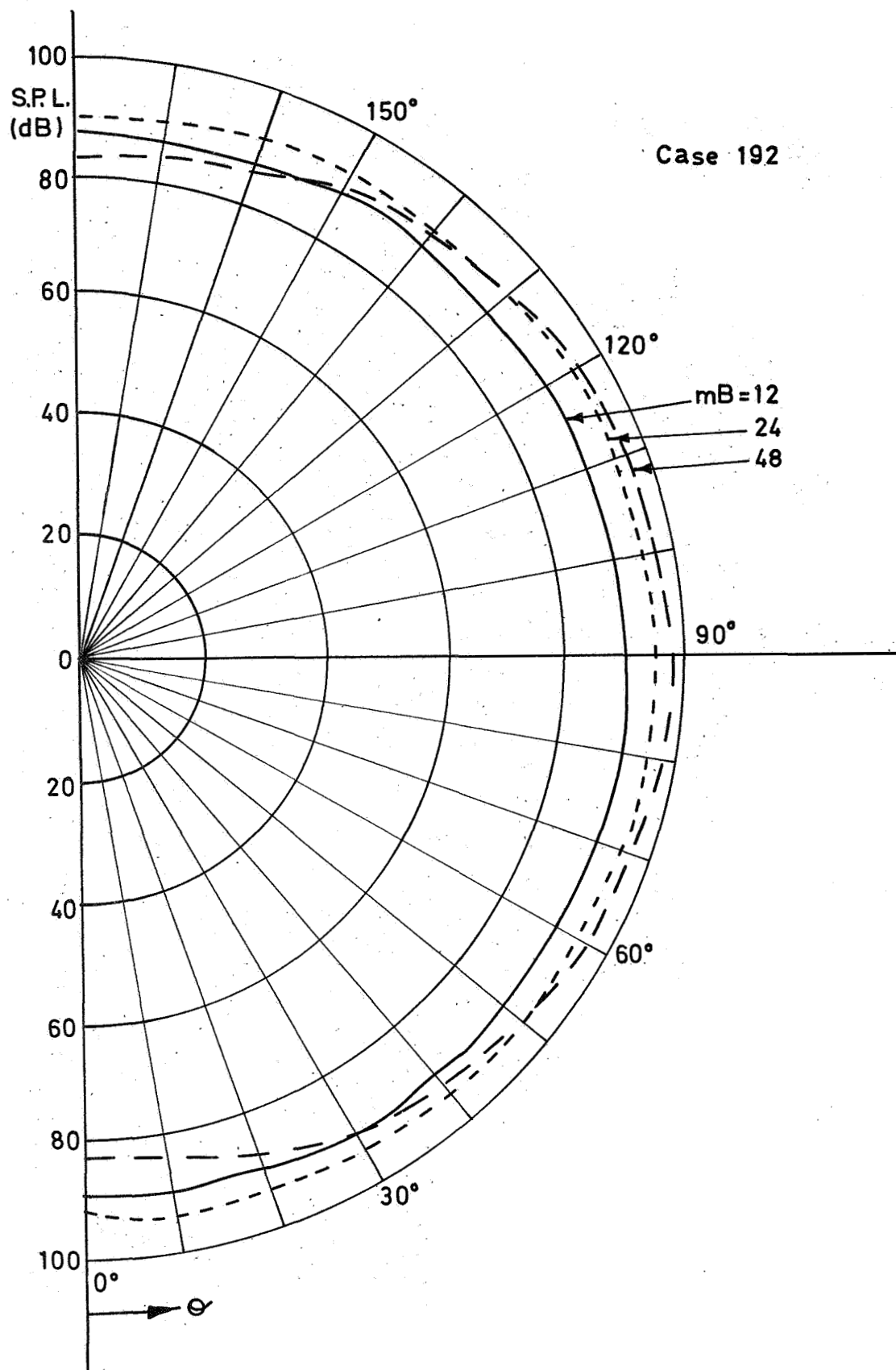


Fig. 2-4-6 Azimuth functions -  $\rho = 1\%$   
polar plan,  $\sigma = -30^\circ$

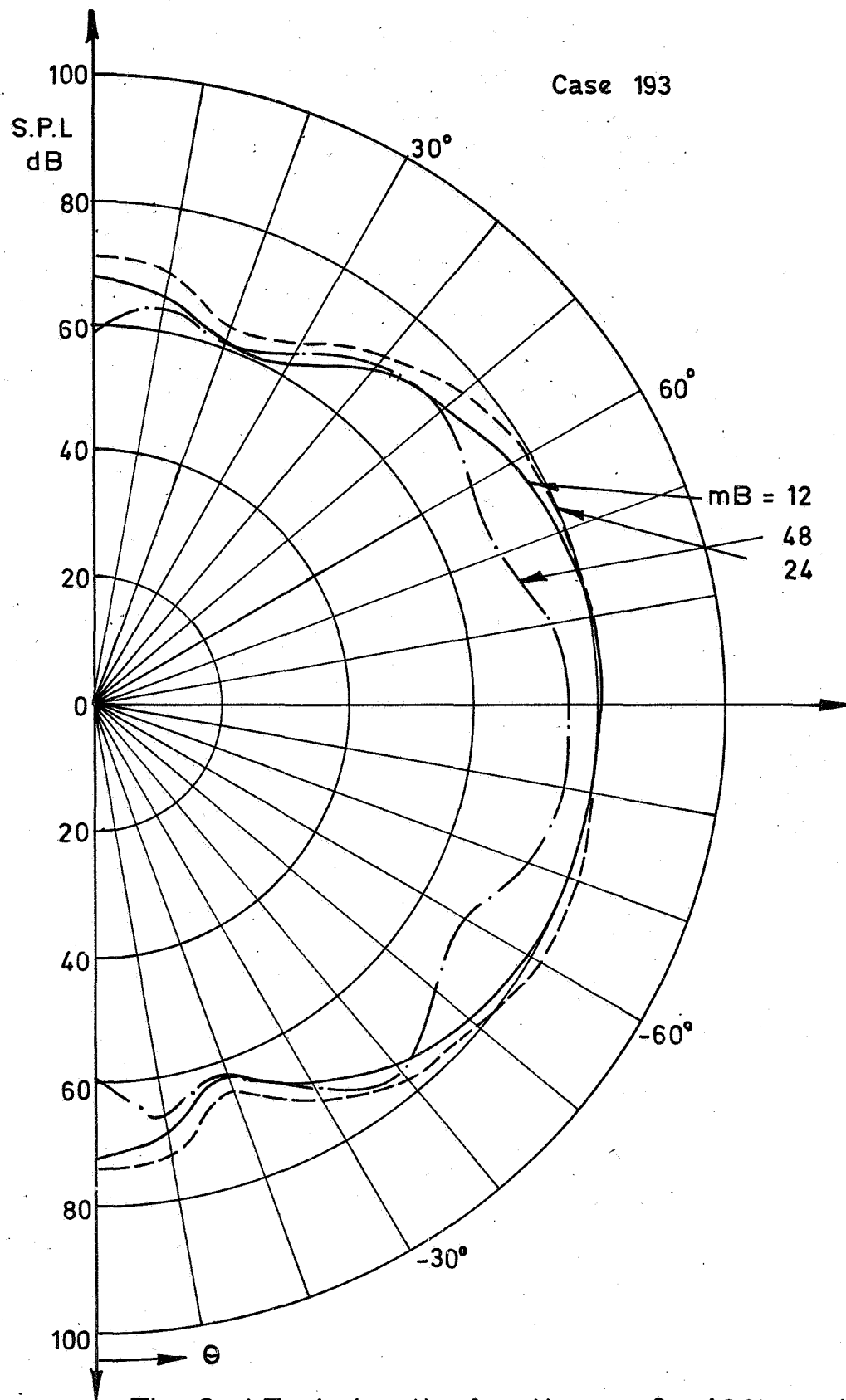


Fig. 2.4.7. Azimuth functions  $\rho = 10\%$  polar plan  
 $\sigma = -30^\circ$

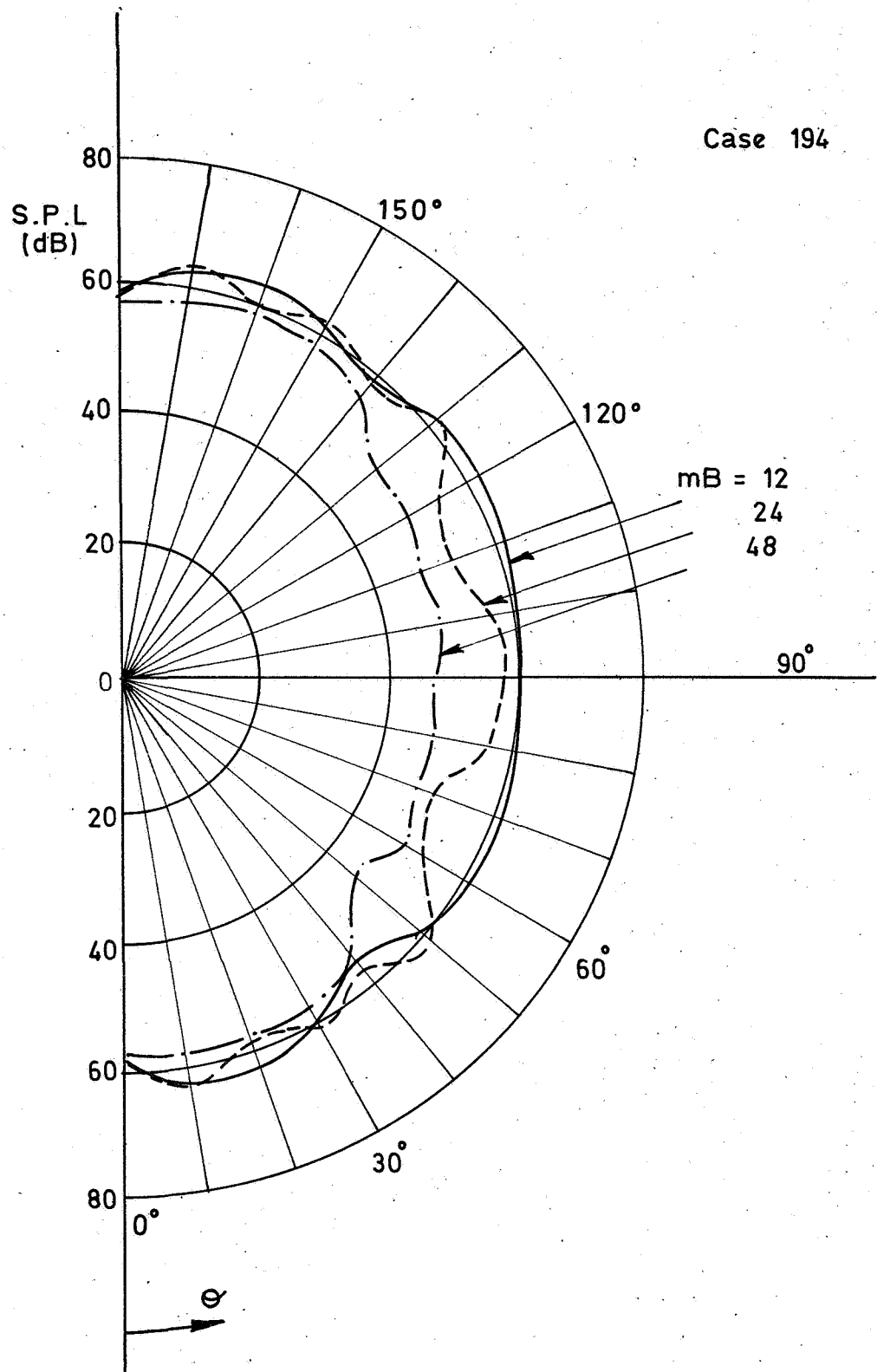


Fig. 2.4.8 Azimuth functions -  $\rho = 50\%$   
polar plan,  $\sigma = -30^\circ$

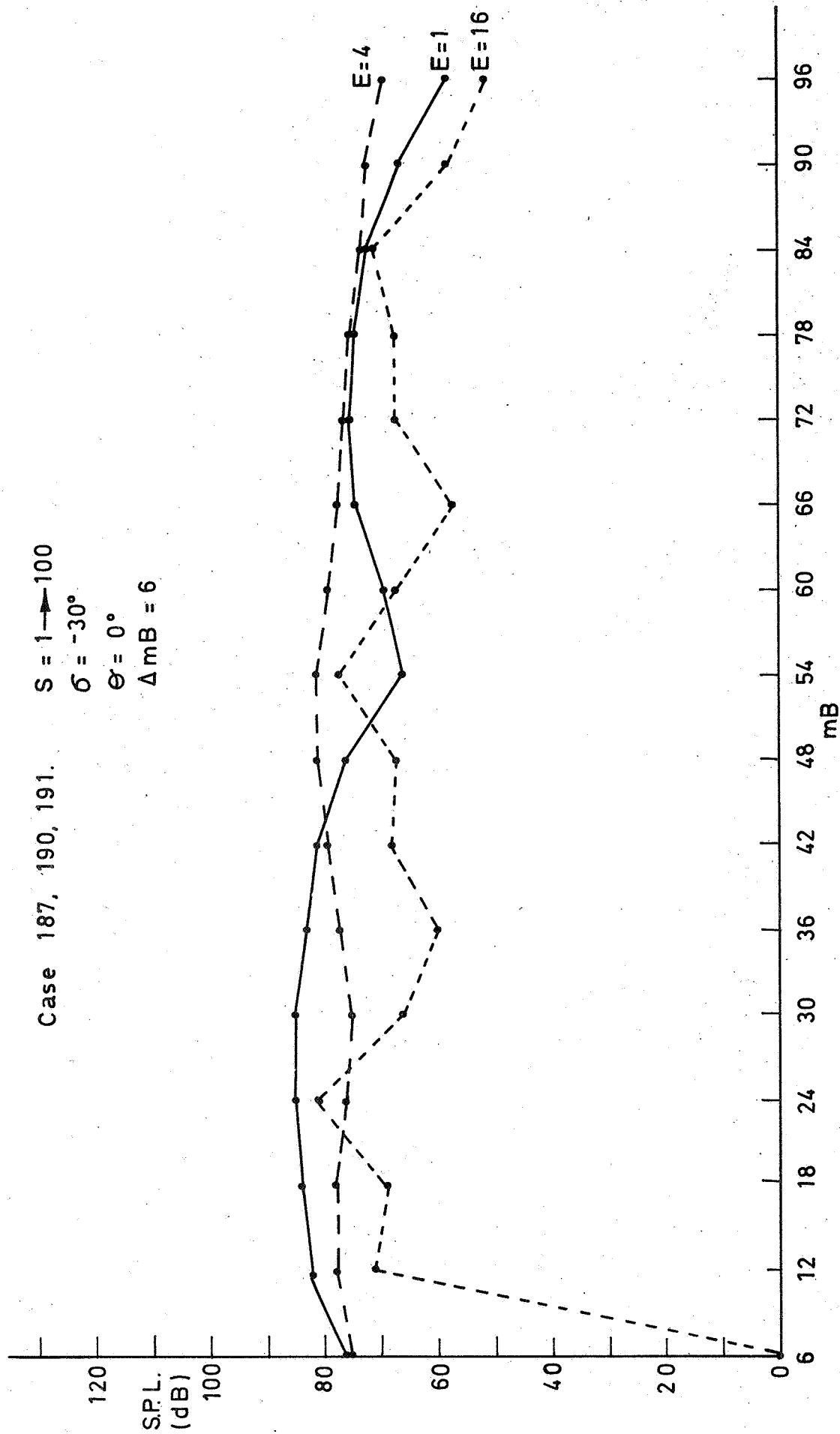


Fig 2.4.9 B.L. Azimuth functions - effect of number of excursions (E) Low res.

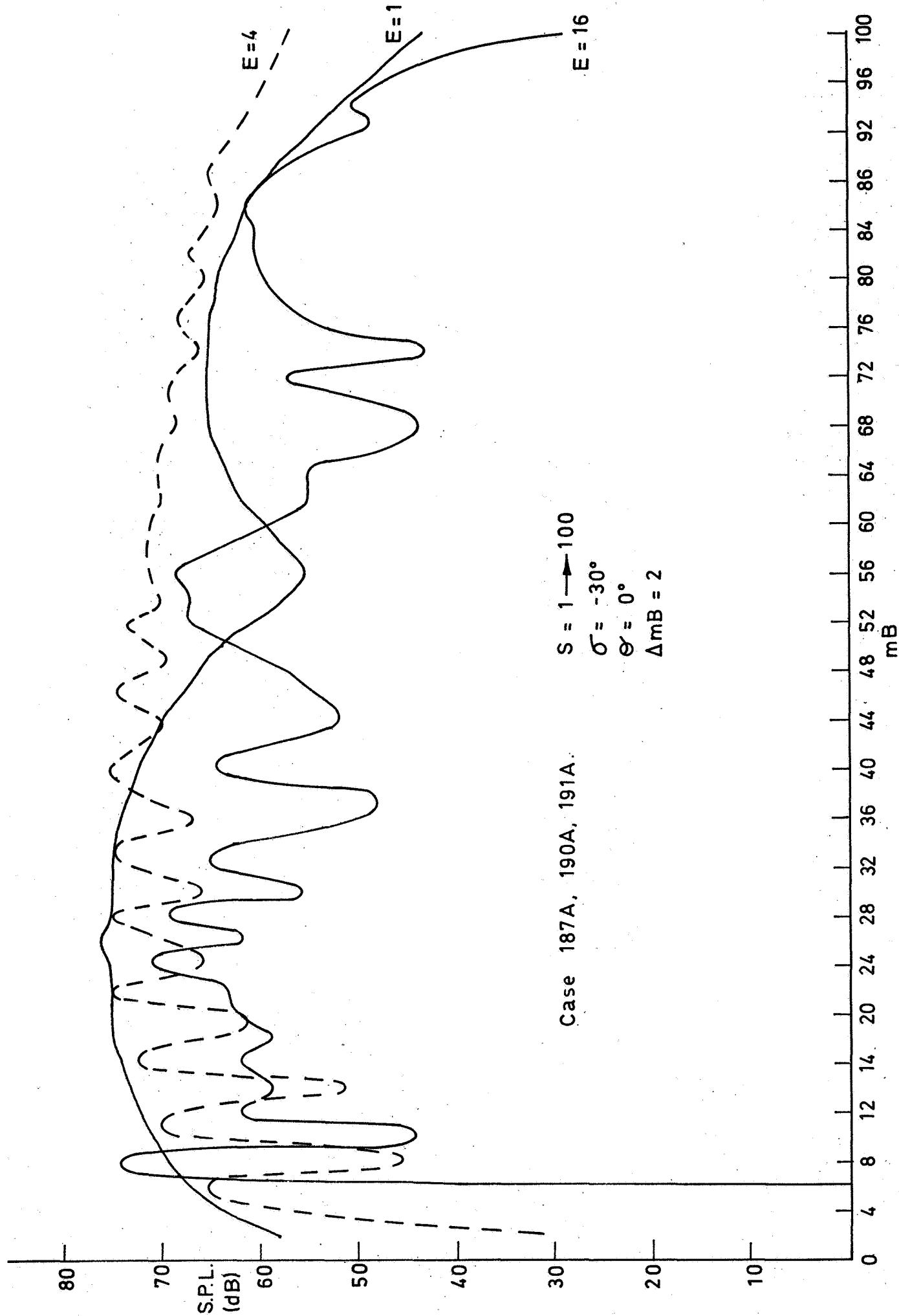


Fig 2.4.10 B L Azimuth functions - effect of number of excursions. High res.

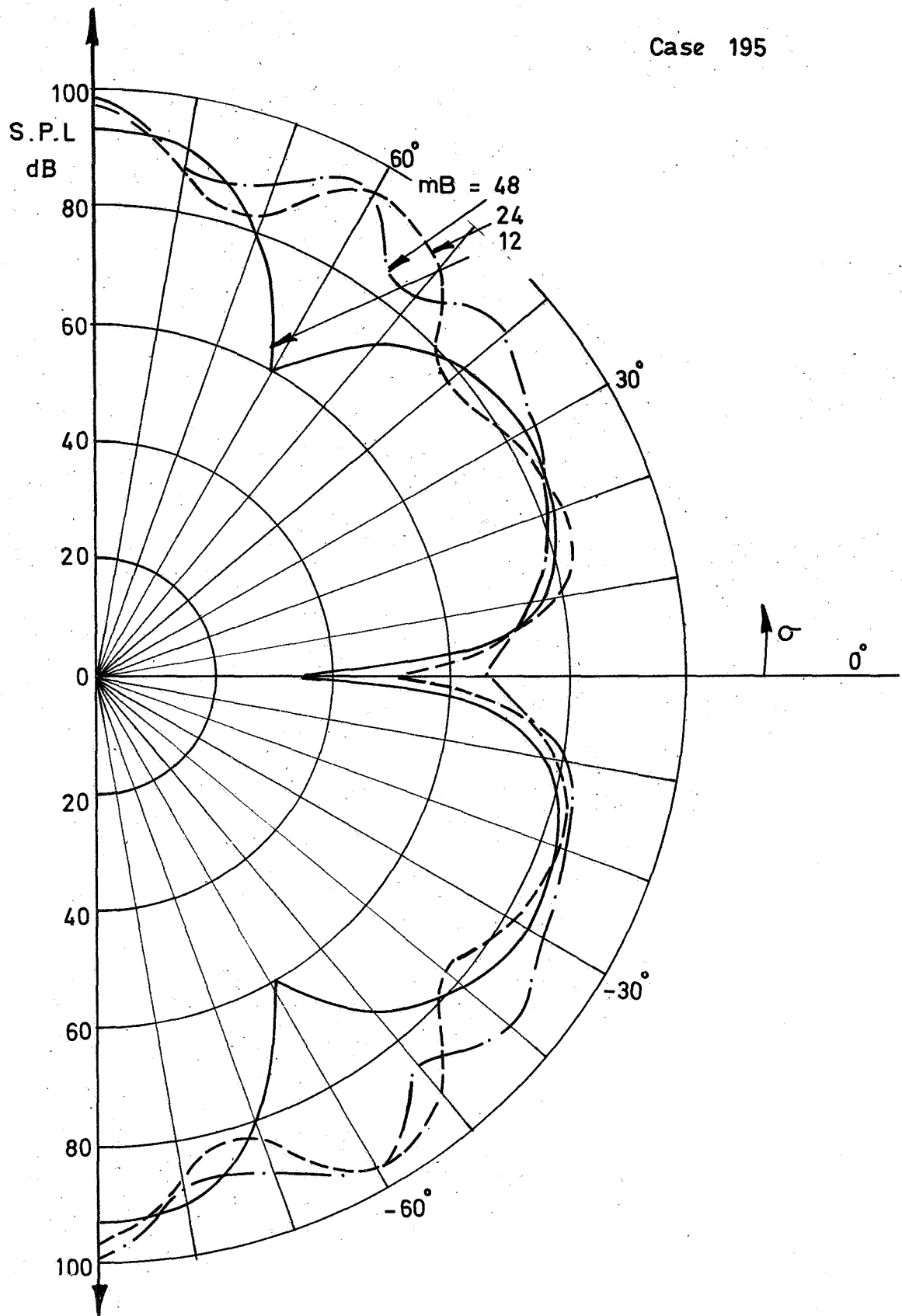


Fig. 2.4.11 Azimuth functions —  $E = 4$   
polar elevation  $\theta = 0^\circ$

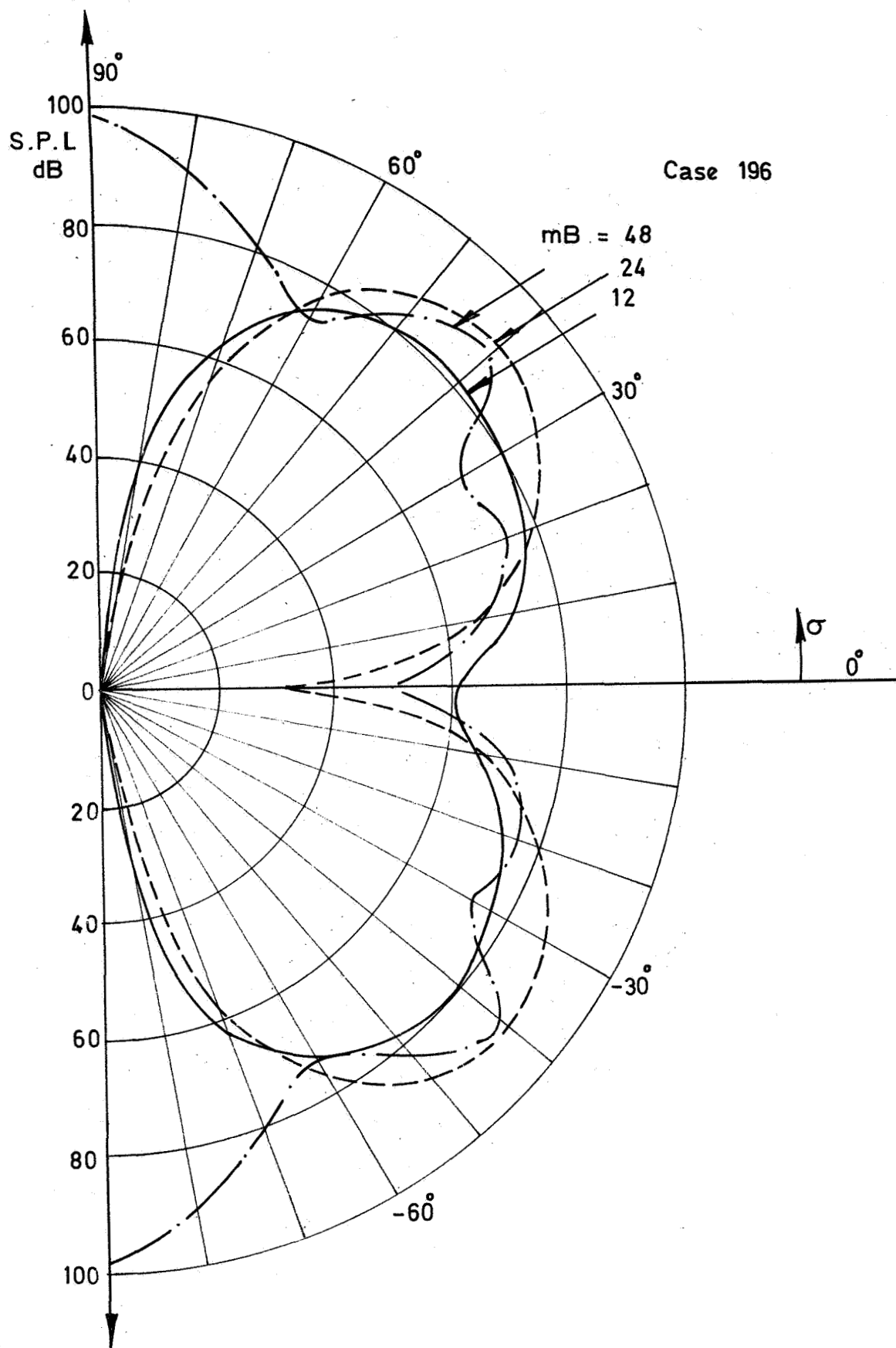


Fig. 2.4.12 Azimuth functions -  $E=16$   
polar elevation  $\Theta = 0$

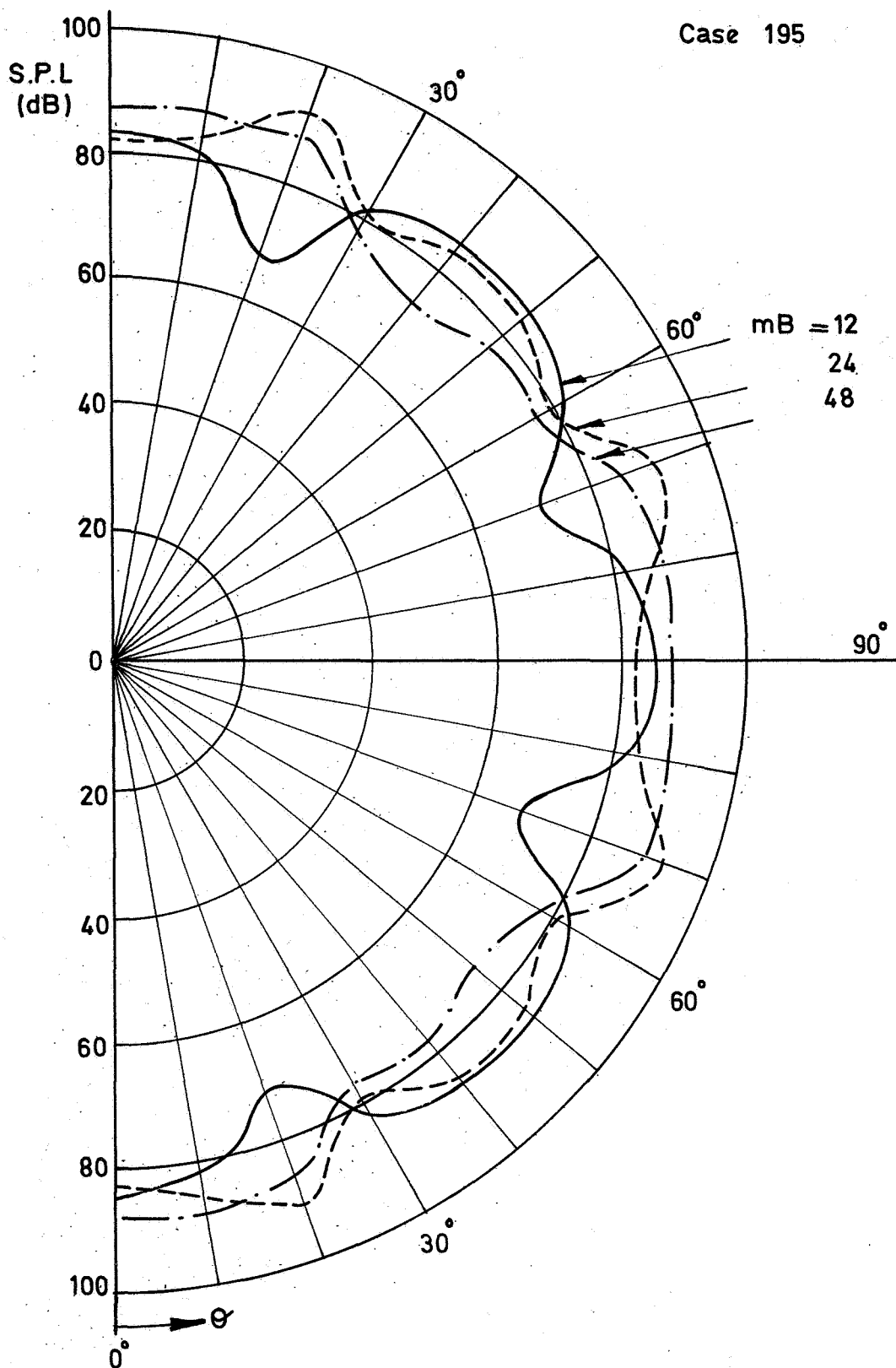


Fig. 2.4.13 Azimuth functions -  $E = 4$   
polar plan  $\sigma = -30^\circ$

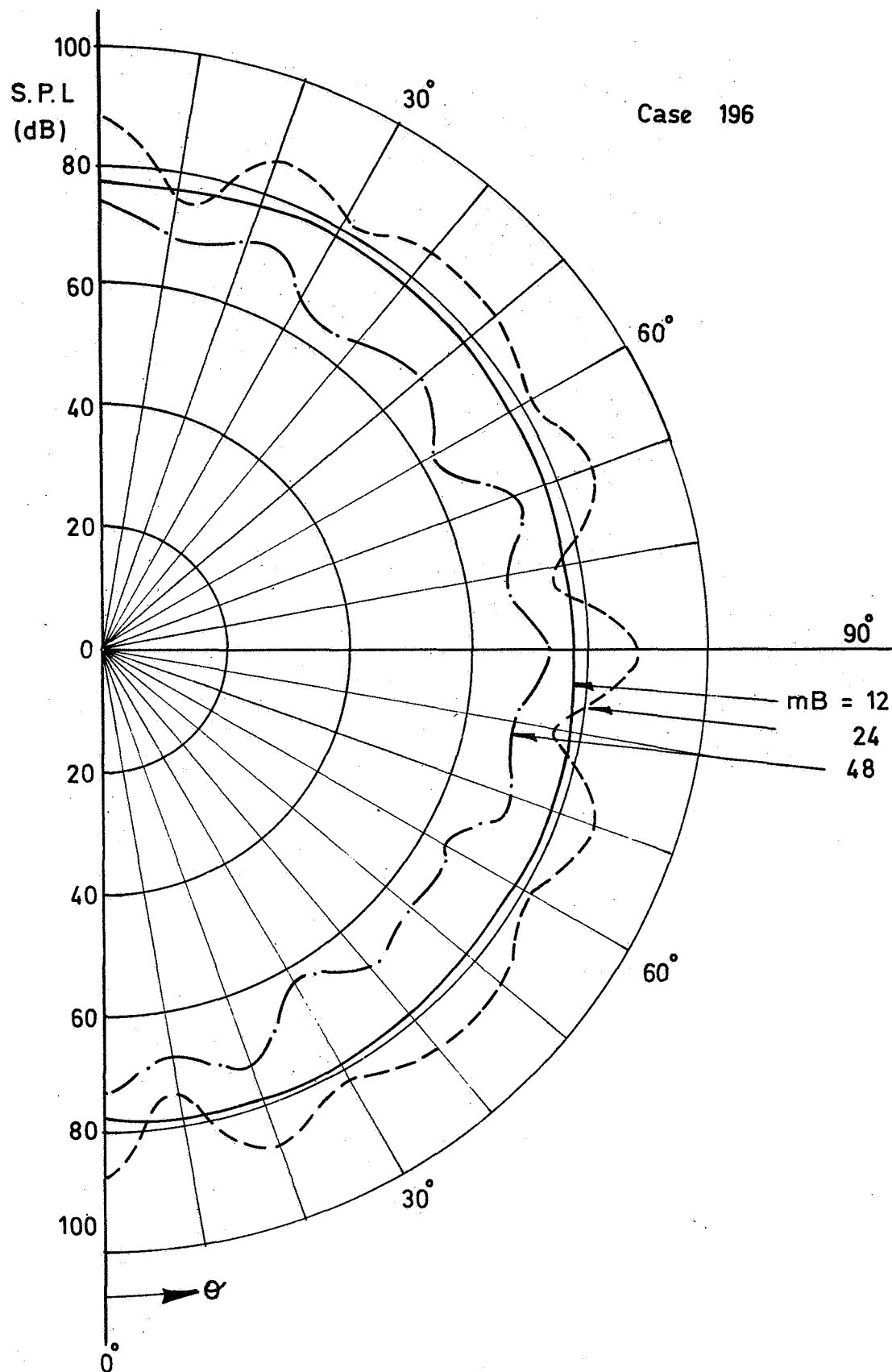


Fig. 2·4·14 Azimuth functions - E=16  
polar plan  $\sigma = -30^\circ$ .

Case 239, 240, 241.

$S = 1 \rightarrow 300$   
 $\sigma = -30^\circ$   
 $\theta = 0^\circ$   
 $\Delta mB = 12$

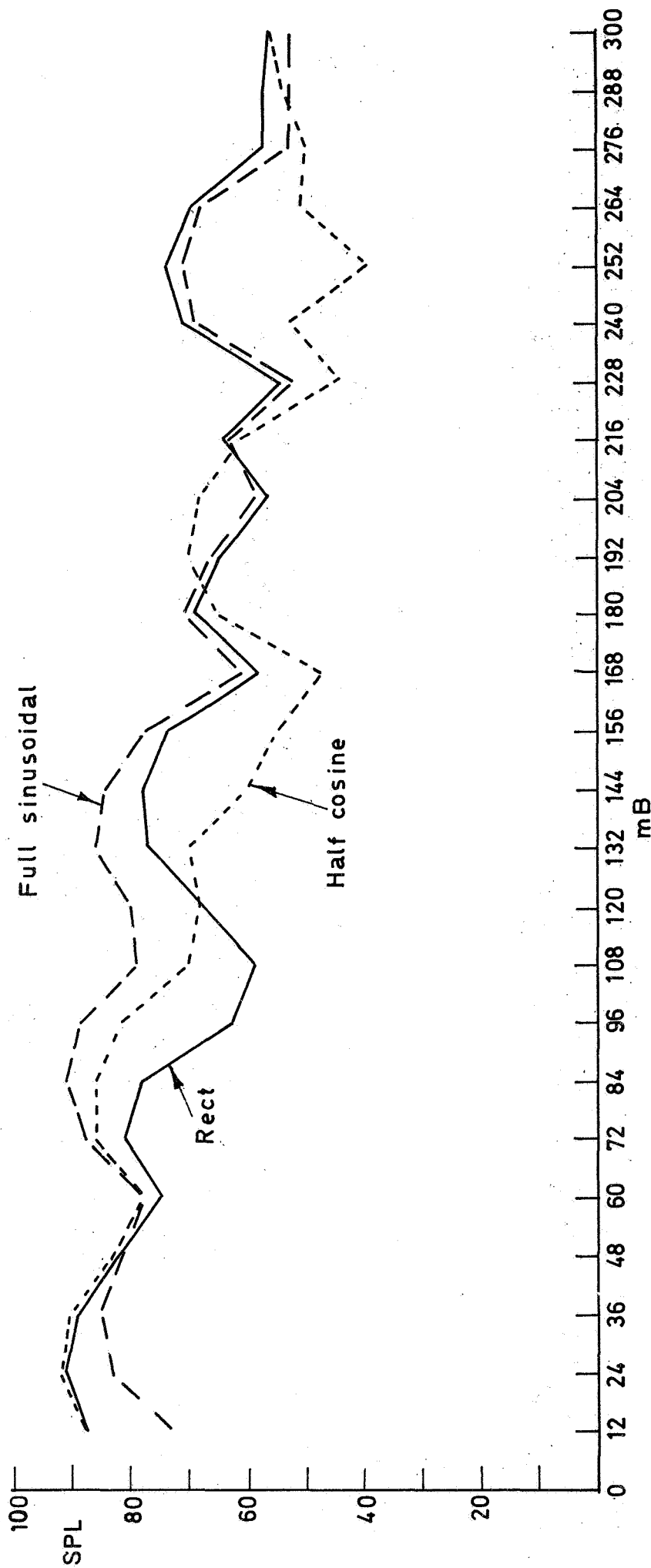


Fig. 2.4 15 B.L. Azimuth functions - effect of type of function Low res.

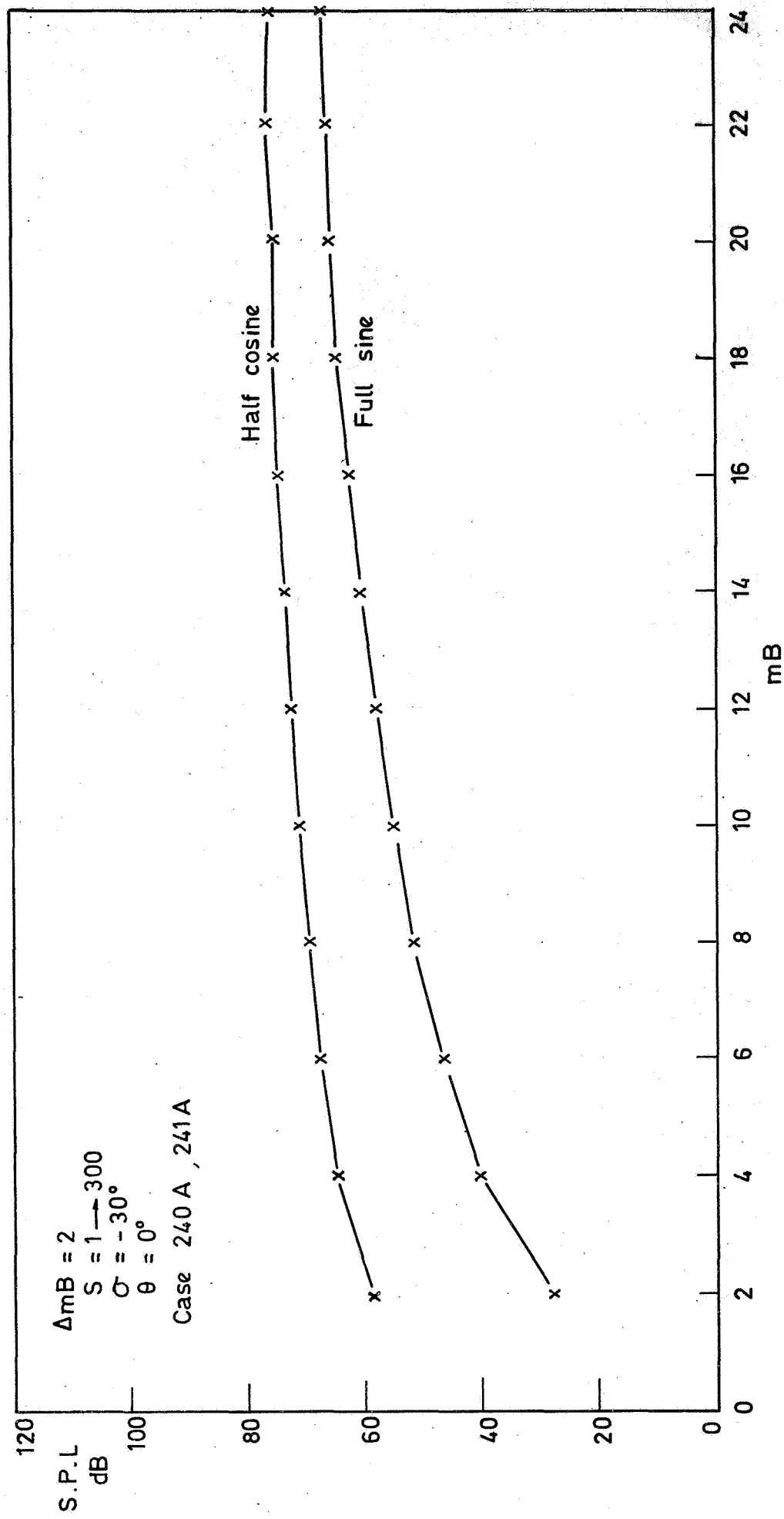


Fig. 2.4.16. B.L. Azimuth functions, effect of type of function . ( High res. )

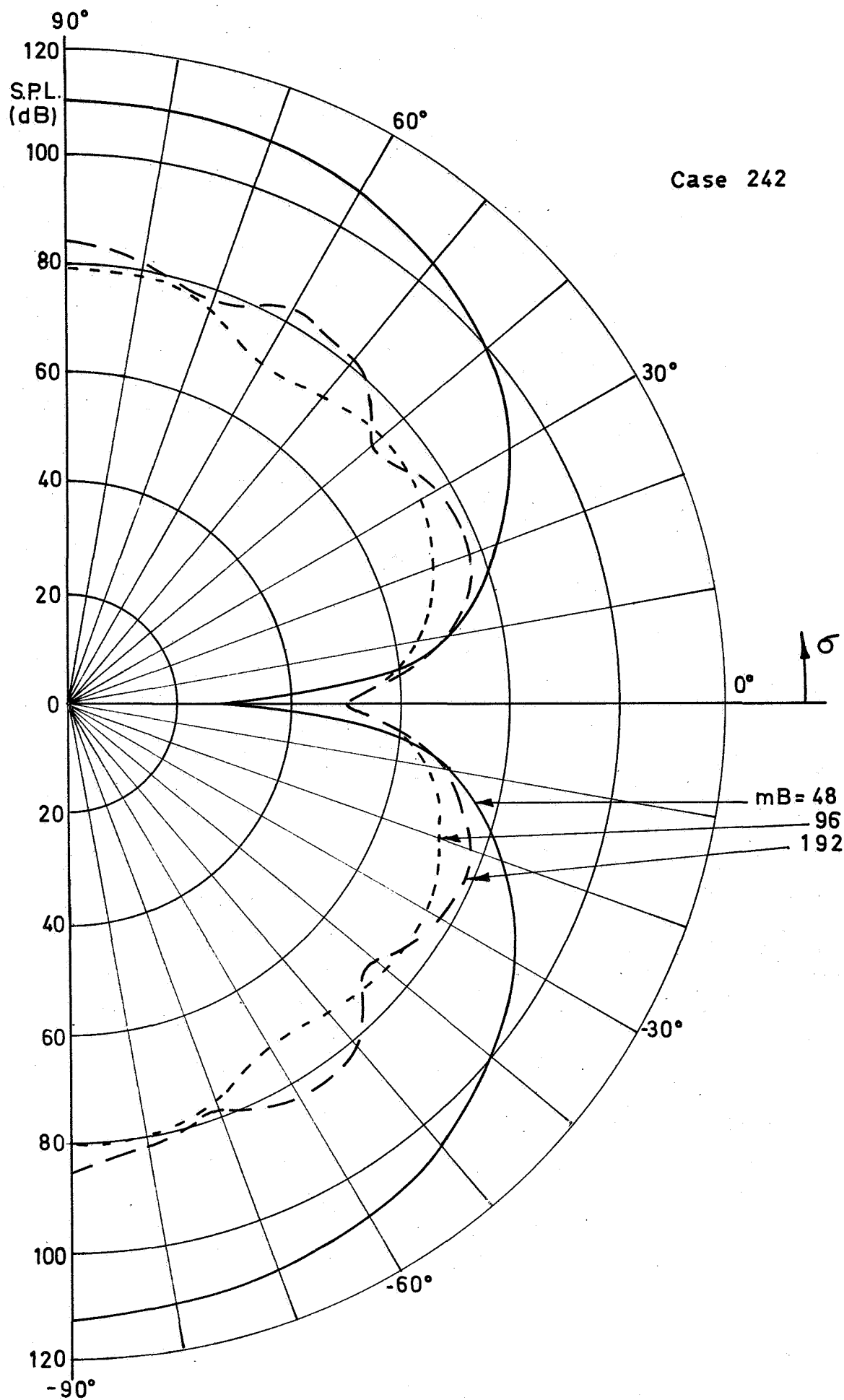


Fig.2.4.17 Azimuth functions  $f_n = \text{rect.}$  Polar elev.  $\theta = 0^\circ$

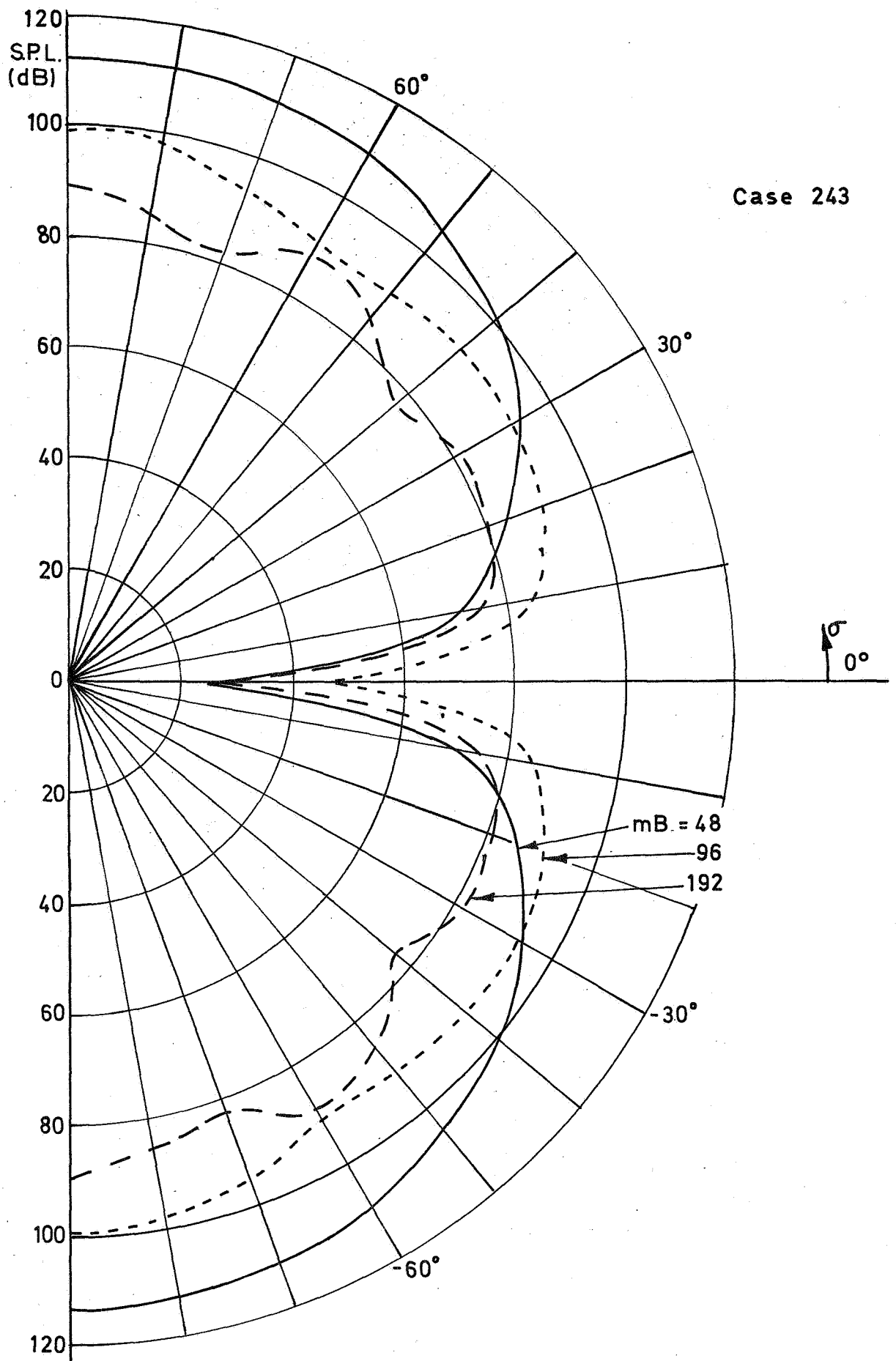


Fig. 2-4-18 Azimuth functions  $f_n = \text{half cosine}$   
polar elev.  $\theta = 0^\circ$

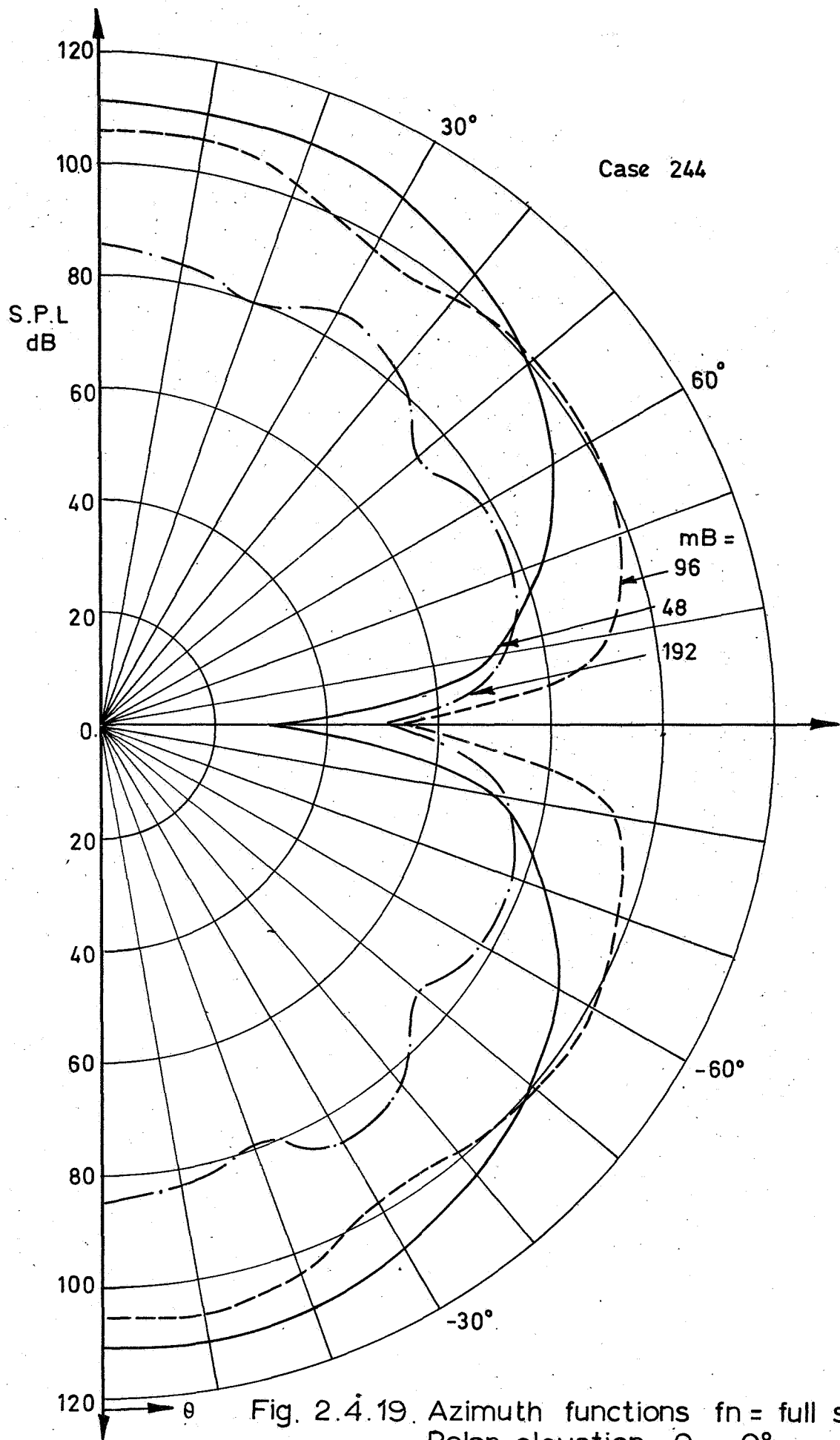


Fig. 2.4.19. Azimuth functions  $f_n = \text{full sine}$ .  
Polar elevation  $\theta = 0^\circ$

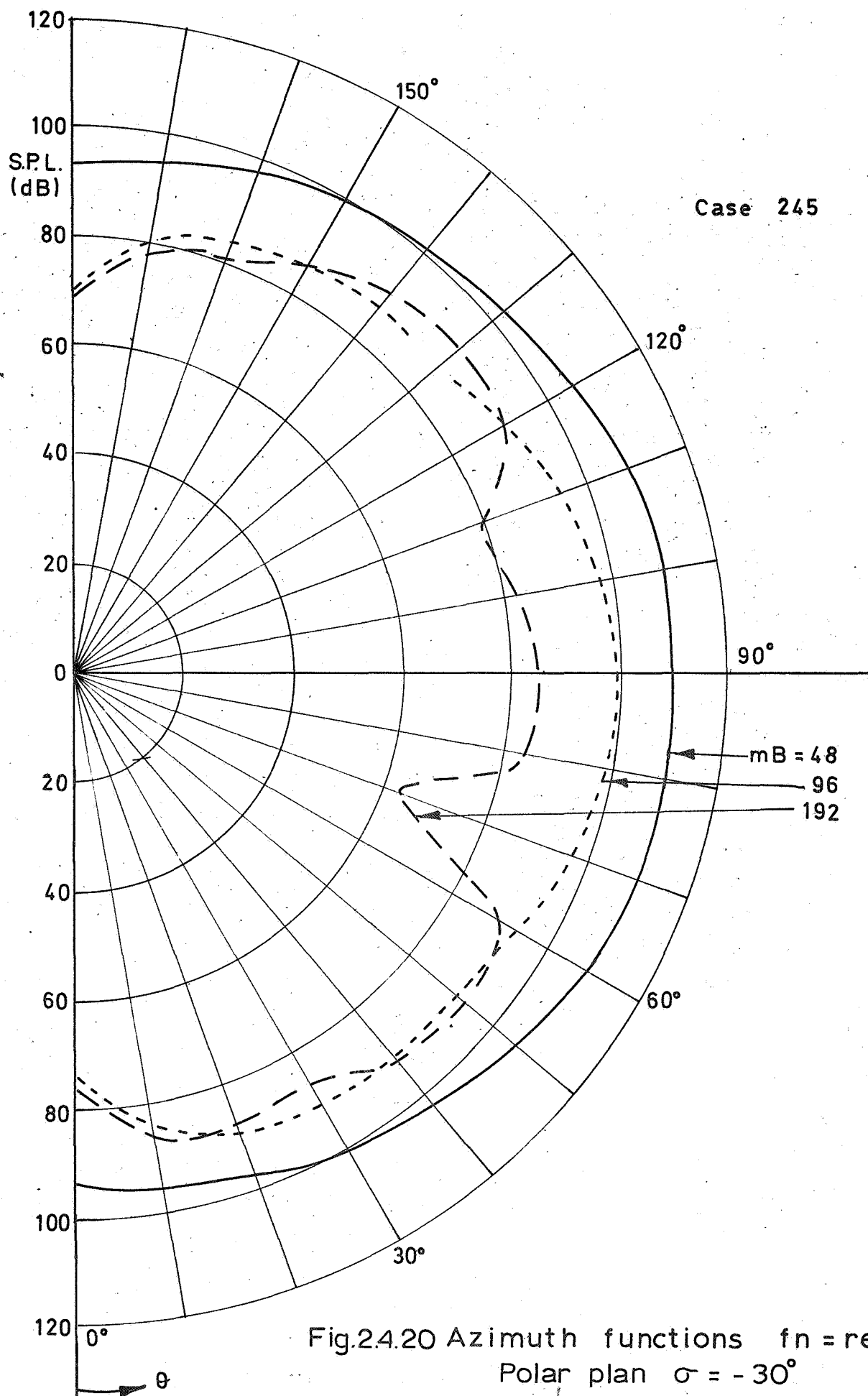


Fig.2.4.20 Azimuth functions  $f_n = \text{rect.}$   
Polar plan  $\sigma = -30^\circ$

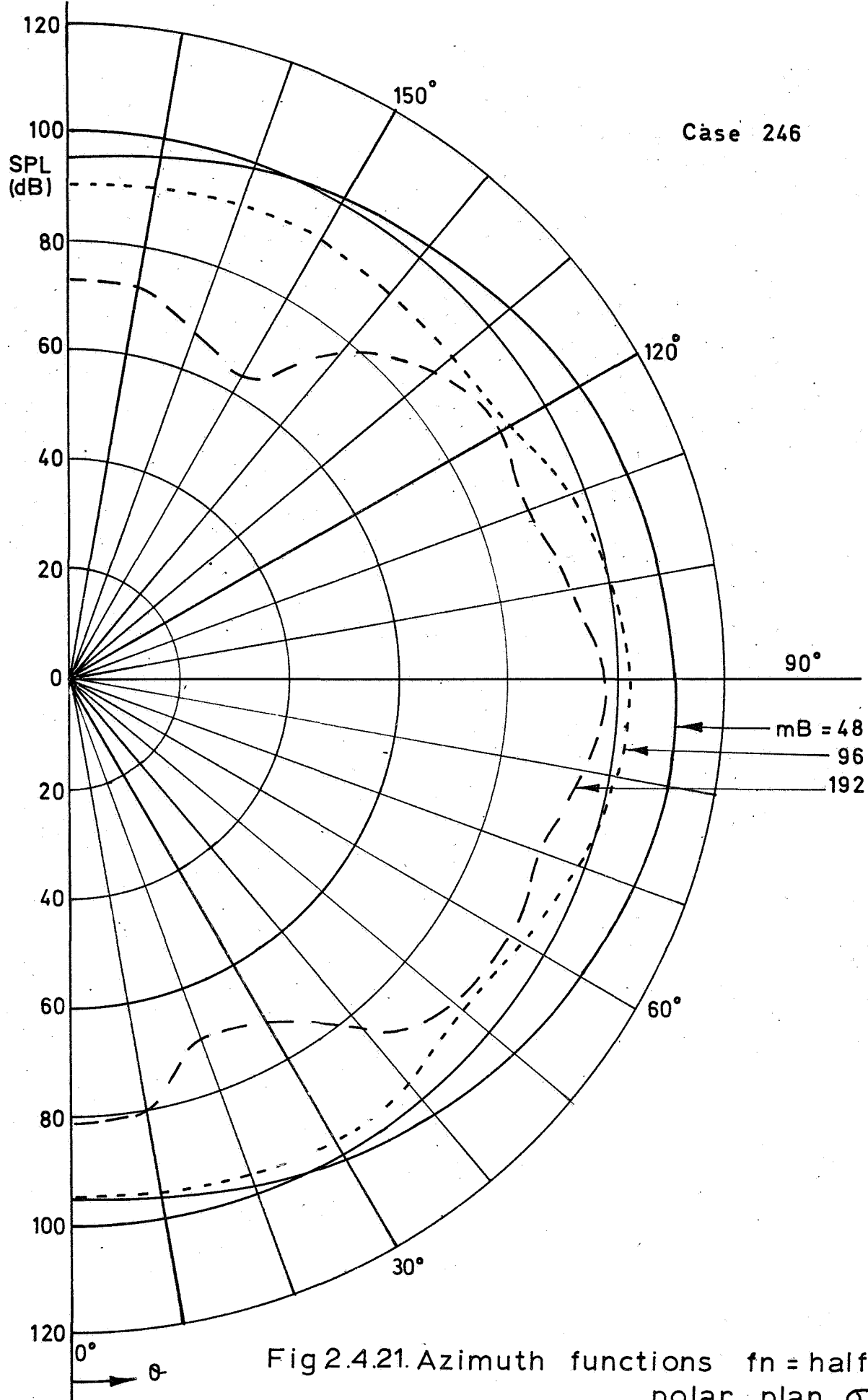


Fig 2.4.21. Azimuth functions  $f_n = \text{half cosine}$   
polar plan  $\sigma = -30^\circ$

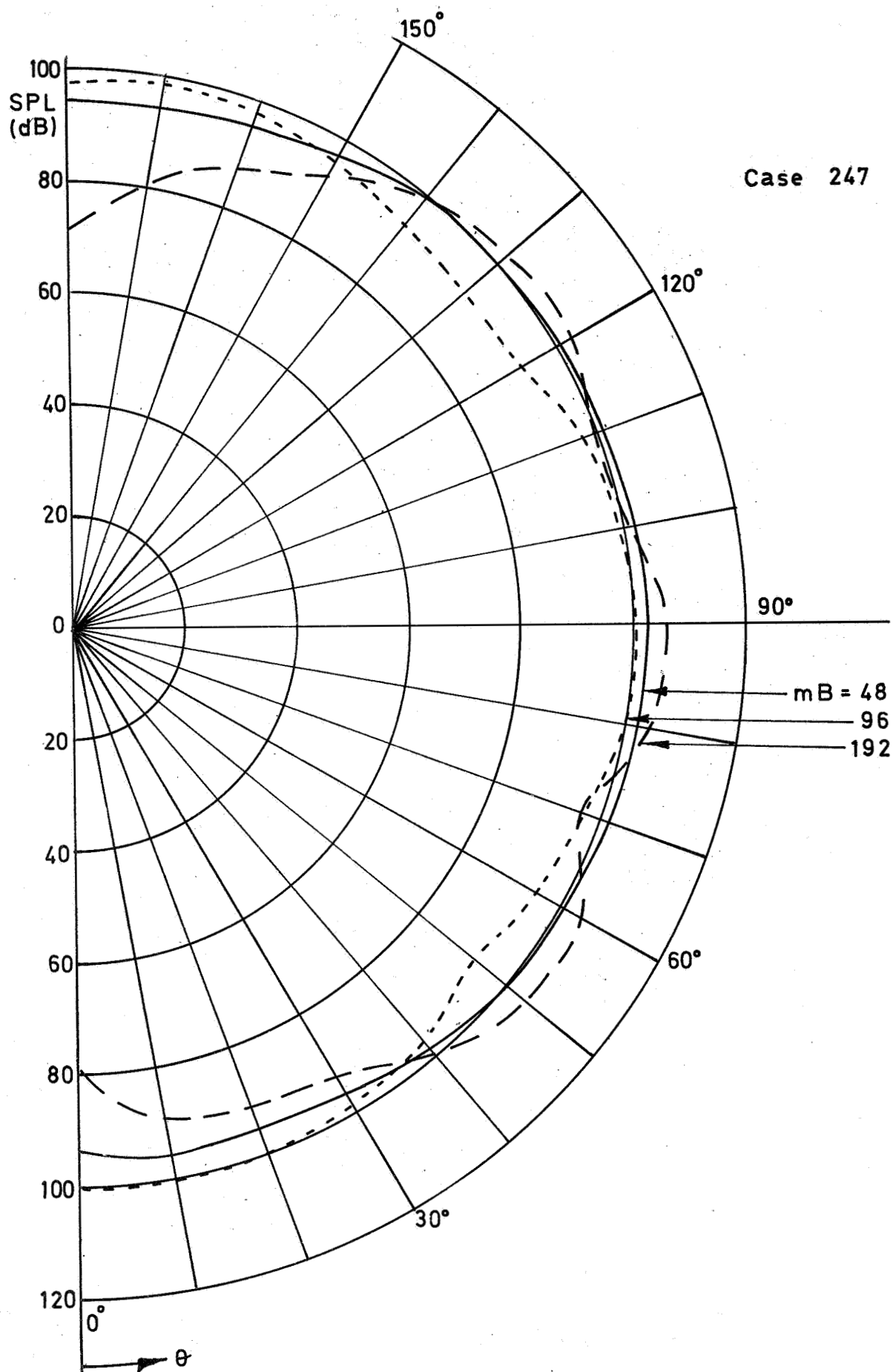


Fig.2.4.22 Azimuth functions  $f_n = \text{full sine}$ . Polar plan  $\sigma = -30^\circ$