HIGH-SPEED DATA ACQUISITION AND REDUCTION FOR WALL STATIC PRESSURES DERIVED WITHIN THE PASSAGE OF A ROTATING ANNULAR TURBINE CASCADE

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Abstract

A data acquisition and reduction procedure for signals from high-frequency-response pressure transducers (KULITE-type) is described. Signals are derived from the DFVLR test facility for Rotating Annular Cascades (RGG). A very simple 'home-made' averaging method for the periodic signals has turned out to be better adapted to the data reduction than a common method on the basis of a FOURIER-transformation. Results derived from both methods are compared. Tests are obtained for probes with and without a protective screen in front of the sensing chip and for both an additional resonator system is investigated. Experiments are carried out at sub-, trans- and supersonic flow velocities. For equal flow conditions the shape of the signals from the different probe configurations are not identical. Some ideas are presented which might explain the deviations.

1. Introduction

In order to simplify the picture for design purposes of axial turbomachines two dimensional flow models are usually used. Cascades of blade row segments are generated either in an annular cascade of high hub-to-tip ratio or by developing the coaxial stream surface of interest into a plane surface as a rectilinear cascade. At DFVLR Göttingen both types of cascades can be investigated experimentally in two different wind tunnels, RGG and EGG |1,2|.

In RGG conditions can occur where the region of nearly two-dimensional flow - termed cernal-flow - is quite small. This occurs for high supersonic relative downstream Mach numbers for cylindrical test-wheels |1| and for investigations on conically shaped test-wheels |3|. For the latter results indicate that the quality of two-dimensional flow decreases with increasing conical flow angle. Therefore, a measurement method should be made available which has the potential of getting more detailed information on the flow.

In RGG this should be provided by using a standard L2F-system to obtain the flow vector. This system was once developed at DFVLR |4| and is now manufactured under licence by POLYTEC, W-Germany. But to account for Mach numbers and losses, for example, it is necessary to measure an additional fluid property. In turbomachinery research, high-frequency-response pressure transducers are commonly used for that purpose.

Numerous investigations are published dealing with the reliability of these measurement devices; information can be taken from |5|. Nevertheless, when both high Mach numbers and high frequencies are to be measured there seem to be still some open questions. Some additional experiments which again may reduce this lack of information have been obtained in the RGG. Some of these results which are more to be seen as preliminary investigations rather than as having solved the problem totally are reported and discussed. Moreover, a brief description of the acquisition and reduction procedure of the high-speed data is presented.

Most of the results shown here are already published in |6| which therefore should be used as an additional source of information.

2. Description of the Experimental Investigations

The complete arrangement of the closed cycle test-facilty RGG - the abbreviation for the test-facility for rotating annular cascades - is described in detail in |1,3| together with its measurement and evaluation method. Since some years investigations are carried out on conically shaped cascades. From the three test sections available the one for 45 degree cone angle is sketched in FIGURE 1.

To get more detailed information on the flow over the blades a device was designed to provide blade surface pressure distribution measurements in different radial sections of the annulus. FIGURE 2 shows a drawing to explain the principle concept of the system |3,7|. The time-averaged static pressure is measured on the blade and is led through a tubing via a disk to the transducer. 48 blades of each test-wheel are instrumented, each with one static pressure tapping only. Altogether, the tappings are in sequence such that for one of the sections, which are at 25, 50, and 75% in blade height direction, measurements at 16 locations in chord direction can be obtained during one test period. For the tests described here two of those tappings are used to provide measurements as close as possible at the tip (at almost 100% blade height).

The two tappings are in the conical chordwise direction located at 70% where nearly maximum pressure differences between the suction and the pressure sides could be expected as is known from tests in EGG |8|. In the very same position different probes of KULITE type are flush mounted to the inner contour of the casing. Minimum tip clearance is guaranteed by an abradable material when tests are run from low to high RPMs. For the tests described here RGG should serve as a periodic flow generator. It is the idea of the experiments that the maximum pressure differences for signals of each test can be compared with those measured by the two tappings on the blade tip. It is not expected that from both measurements methods exactly the same results are evaluated but - as a working hypothesis - they are expected to be in the same order of magnitude.

For these tests pressures are of interest only as peak-to-peak differences. This avoids taking care of the well known temperature drift of the transducers which is a widely discussed problem, see |5| where some references are given. The signals from the transducer, i.e. output versus time, represent the wall static pressure distribution in the pitchwise direction of the passages measured in the machine-fixed absolute system. In FIGURE 3 the tip section area of the test wheel used is developed into a plane surface. To provide the desired flow conditions for this hub-section cascade consisting of 80 blades the test-wheel has to be driven |3|. When a blade passes in front of the transducer, the maximum difference in output occurs. Using the coefficients of the static transducer calibration the corresponding pressures can be obtained.

Assuming ideal conditions at blade tips, i.e. no clearance between blade and casing, infinite diameter of the probes head and inertial free probe response the trace versus the blade from pressure side to suction side has to be of square wave type. Such a hypothetical trace is sketched qualitatively in Figure 3 (dotted line). For this case a second cross-check would be possible, i.e. the periodicity of the signal represents the geometric conditions at the tip which also means that the duration of the pressure plateau of the square wave has to correspond to the width of the blade, b, while the remainder has to correspond to the flow channel, (s-b). For the shapes of the latter no prediction is possible because they do depend on flow conditions. Because such an ideal trace cannot be expected from the tests, b is to be taken from the time-difference of the maximum to minimum output, see Figure 3.

First tests described in |7| were carried out with a KULITE XCS-093-15 PSID transducer with an outer diameter of 2.36 mm, probe 1 in FIGURE 4. The differential pressure transducer is referenced to the static pressure in the first downstream measurement plane, Figure 1. The same procedure is used for the transducers of probe 2 to 5. This position is chosen arbitrarily but ensures that the pressure difference is always within the required range without additional regulations.

As a general remark it should be pointed out that the results for probe 1 have not been satisfactorily enough to use it for standard measurements in the future.

Obviously, there are some reasons which may be responsible for the deviations from expected results and which, of course, are true also for succeeding probe designs: the complex secondary flow field near the measurement point; the transducer is not 100% flush mounted but some tenth of a millimeter apart from the inner contour which causes a small resonance volume; the two pressure tappings on suction and pressure sides of the blades are not exactly in the same axial position; the diameter of the tappings on the blade of 0.3 mm is smaller than the sensing area of the transducer.

Nevertheless, the main reason for deviations is thought to be due to the screen of the transducer. This screen, the only purpose of which is to protect the sensing chip mechanically, consists of 18 holes of about 0.1 mm diameter each drilled within a circle of about 1.7 mm. No tests have been done on the influence of the number of holes. But it is obvious that succesively closing more and more holes might easily result in differently shaped output signals. Due to the small dimensions of the transducer and the related mechanical restrictions such tests seem to be impossible to be provided.

Further tests have been carried out and are reported here for probes with different transducers smaller in diameter, 1.53 mm, to fit better into the geometric hardware conditions, see Figure 4. Two further transducers have been investigated. The chip of the first one, XCS-061-15 PSID, has been protected with a screen consisting of 9 holes of 0.1 mm each drilled within a circle of about 1.0 mm. The second one, XCS-061-05 PSID, has been unprotected. Thus the chip has sensed pressure fluctuations directly and the sensing area has the dimensions of the chip itself. It is thought that the different pressure ranges of 15 and 5 PSI will not restrict any conclusion drawn from the investigations.

Furthermore, for both transducers different kinds of cavities have been investigated to get some information on resonance problems. This has been done in two ways: firstly, simply by setting the transducers up to 2 mm back from the almost 100% flush mounted position of the casing (< 0.3 mm). Secondly, a cylinder with a hole of 0.3 mm at its end is fixed in front of the sensing area of the probe, Figure 4, thus simulating a protective 'screen' - or a double-screen for probe 3 - with the very same diameter as the hole of the tubings on the rotating test-wheel.

3. Data Reduction

In FIGURE 5 a photo taken from an oscilloscope for an arbitrarily chosen signal is shown. From the 80 signals of one test-wheel revolution 11 are to be seen. It is obvious that the basic frequency is almost equal for all passages and the shapes of the cycles are quite similar.

Because such high-speed data cannot be transferred on-line with conventional electrical connections over a distance of about 400 m from RGG to the research centre's central computer the following procedure is used: data is stored on a magnetic tape of a recorder STORE 7D, RACAL-THERMIONIC, UK and after tests have been finished the signals are digitized using this recorder in connection with a high-speed A/D-Converter GMAD-1, PRESTON, USA, |9|, controlled via a Process Computer PDP 11/40, DIGITAL, USA. Both the latter are located in the computer centre. Finally, the data are available on the IBM 4381 computer for further reduction.

First, tests were carried out to check the reliability of the recorder and the converter by producing well-defined signals with the aid of a wave generator. Sine waves which simulate transducers signals from RGG best were reduced perfectly.

In FIGURES 6 and 7 results for a low and a high Mach number are shown after being digitized using the same tape speed as during acquisition and 62.5 kHz sampling frequency. On top of the pictures the total content of the file is plotted. On successive diagrams the shape of the cycles are more clear to be seen by expanding them in abscissa direction plotting the first half of the previous one. Thus on bottom of the figures the first 7 and 9, respectively cycles stored in the file are to be seen. From the signals on top it can be seen that a 'pending' occurs, demonstrated by the dashed line in Figure 6. The reason for this is unknown so far. It can be due to the transducers reference pressure located in the downstream flow field which at least may fluctuate slightly. By using a source of constant pressure as a reference an easy check could be provided. Because the peak-to-peak differences are quite constant, for example in case of Figure 6 about 18 mmHg (2.4 kPa), this 'pending' seems not to be related to imperfections of the hardware.

Such signals would usually be reduced by a FOURIER-transformation which is standardly available in many computers and frequency analyzers. The following procedure was applied to the traces: first such a transformation was performed; then from the prominent frequency the blade passing period equal to the ratio of pitch to test-wheel speed was accurately computed; over this period an averaging process was performed which reduced the whole periodic trace to one averaged trace for one pitch.

But it turned out that the reduced signals were 'washed out' especially in the region of maximum and minimum output. This result was almost independent of whether digital filters were used or not. In FIGURES 8 and 9 results for the frequency spectra as well as the reduced time averaged signals are given for the traces shown in Figures 6 and 7. The blade passing frequency is in good agreement with the one recorded during tests using a frequency counter. It is to be seen that additionally some harmonics are evaluated.

The differences in amplitude for Ma w2 = 0.5 is only about 10 mmHg (1.3 kPa) which is only 56% of the one from the single traces. Geometric test-wheel conditions represented on the time axis are not as accurate as single traces are.

Another reason for the deviations could be that averaged signals are based only on a maximum of two revolutions of the test-wheel, because for those investigations a larger buffer for the A/D converter was not available |9|. By using signals from additional revolutions which are available on the tape a more realistic behaviour can be expected. It was not investigated whether this is true or not, although it could be done by digitizing the recorded signals step by step storing them in seperate files which later could be copied to a single file. This procedure would lead to an enormous amount of data.

Because these results are not satisfactorily, another code for reduction is applied to the signals. This very simple 'home-made' method turns out to be better adapted to the problem: from the 5000 values available in one file, see examples from Figures 6 and 7, an averaged value is calculated. Values which are obviously wrong (runaway) are set to the averaged one. This quantity is used to determine the number of cycles included in the file. It is assumed that whenever a value on the steep gradient line, which occurs when a blade passes the transducer, see also Figure 3, is less than the averaged value a new cycle begins. The first value of a new cycle is added to the previous cycle and simultaneously the last one of the previous cycle is added to the successive one. Consequently, the first and the last value of a cycle now occurs twice in two different cycles which then certainly contain information for at least one pitch.

From each cycle the averaged value is calculated and is set to 'Zero'. Therefore, signals are now such that they are above and below the abscissa. This trick cancels the 'pending' and can be used, because for these tests only pressure differences are of interest. In the next step the number of time steps of each cycle is determined. For those which are equal in time step number pressures are averaged by calculating mean values for each time step.

At this stage this procedure cannot be applied to compute a single cycle on the basis of all averaged traces easily, because they do consist of different numbers of time steps. To provide this, another simple procedure is used: averaged traces of equal time steps are normalized on the abscissa to unity, i.e. the cycle time is normalized to unity. Each cycle is then divided into 100 time steps. For these small constant time steps the ordinate values are calculated assuming a linear relation between adjacent pressure values. Here, it may occur that traces have a slight offset against each other in 'time' which has to be corrected. Then, for each time step a mean value of pressure is calculated each of them weighted with the number of traces from which it is averaged. This leads to the final result, i.e. a single trace averaged from all the cycles from one file. The frequency can than be determined by dividing the time steps for all cycles by the number of cycles by taking into account the tape speed and sampling rate.

As a cross-check for this procedure analytically evaluated periodic functions were reduced. As a result, a perfectly averaged cycle from each of these curves appeared.

4. Results

First results obtained with probe 1 are discussed in |7|. For a downstream Mach number of 0.53 the peak-to-peak pressure difference is in quite good agreement with the steady pressure difference,Δp, measured in the relative system. But for increasing Mach numbers the discrepancy increases, compare circle and cross symbols in FIGURE 10.

From the measurements in the relative system also those are examined which are obtained at 75, 50, and 25% of the annulus height. Both tappings at these 3 sections are not aligned to the axial plane of A-B-C, Figure 3, but are to the left and right of it, respectively. The trends of the results, curve 2 to 4, are similar to the ones measured at the blade tips, curve 1.

In |6| results derived from the 'home-made' method are shown to demonstrate the dependance on number of averaged signals, sampling frequency and tape speed. There it is to be seen that the general shape of the signal is almost independent of these parameters even if only a few cycles are averaged. From this it is concluded that for future tests data can standardly be aquired with a tape speed of 60 inch/sec and can be digitized with a sampling frequency of 62.5 kHz using this speed. For the final results this means that traces are averaged from about 100 to 200 cycles, i.e. up to 2.5 revolutions. Single cycles consist of about 30 time steps.

A simple qualitative check is possible by comparing photos of a trace taken from a storage oscilloscope with a digitized signal from the same flow condition. Their general shapes are very similar |6|. The blade passing frequency derived from the data reduction procedure deviates only as slightly as the one from the FOURIER-transformation does in comparison to the one measured directly during tests.

In FIGURE 11 a comparison between the 'home-made' method and the results from the FOURIER-transformation is given for the signals from Figures 6 and 7. The comparison shows that for both the output and the characteristic in time (pitch)-direction the described procedure leads to a trace the shape of which fits quite good into the shapes of the digitized cycles.

With the new probes investigations were carried out on resonance problems due to small cavities. This was simply done by running tests for equal flow conditions but different distances of the probe heads (probes 2 and 4) to the blade tips. Differences in the general shape of the traces have been observed for the different probes. But if results for each probe are compared only minor deviations occur.

Therefore, the miniature cavity shown in Figure 4 is added to the probes head because for the comparison it seems to be necessary that both the chip of the transducer and static pressure tappings are integrating over almost the same area of the flow field.

Tests have been run using probes 2 to 5 for 11 different flow conditions which are chosen to cover the sub-, trans- and supersonic flow conditions. From tests described in |3| it is known that, for the cascade under investigation, values for both absolute and relative Mach numbers are in the same order of magnitude. Conclusions are drawn here on the basis of results from Mach numbers of about 0.5, 1.0 and 1.3, FIGURES 12 to 14. For explaining the different results of the four probes they are plotted for each Mach number such that almost optimum overlapping regimes for the traces occur. The remaining deviations are than used to argue about the quality of the probes output.

From the Figures it is to be seen that considerable deviations occur from the suction side of the blade towards the passage and minor but again remarkable ones from the passage towards the pressure side. For the remaining parts of the cycles areas do exist where results are quite similar. But with increasing Mach number the regimes of similar trends are decreasing.

The deviations of the signals at both their minima and maxima are assumed, to be first of all related to minor but different tip clearances during the different tests which hardly can be provided to be always exactly equal. In addition, the results for the different resonator systems under investigation have not been expected to be equal or even similar.

To get informations on of what might be due to these resonances within the cavities a plot similar to the one of Figure 11 is provided, FIGURE 15. Pressure differences obtained from both frames of reference agree best with results of probes 4 and 5, curve 8 and 9. It may be seen that up to Mach number 1.0 results now agree well with curve 1. The unexpectedly good agreement at subsonic speeds contrasts with the supersonic case. This leads to the question as to why such large deviations occur at Mach numbers > 1. This is possibly due to the supersonic flow conditions which partly do occur in the passage. The corresponding shocks may cause some kind of blockage at the probe head so that the chip may not be able to see pressures correctly.

In FIGURE 16 static pressure distributions derived for an isentropic downstream Mach number of 1.3 and for geometric conditions according to blade tips from a 3-D EULER-code |10| are plotted as pressure differences versus pitch from 0.0 corresponding to location (C) in Figure 3 to 0.7 corresponding to (B). The total pressure is almost equal to the one of the tests. Quantities at (C) are arbitrarily set to 'Zero'. In this diagram results in axial direction are shown from plane '31' to '40', see Figure 3. The measurement plane is represented by '35'. The trend there is more similar to the one derived from probe 5 than the one from probe 4, see Figure 14. Obviously, the trend is different further downstream beginning at plane '37'. The static pressure difference derived from theory of about 102 mm Hg (13.6 kPa) is more close related to the experimental results obtained from the relative system, see full circles in Figure 15. Unfortunately, additional cross-checks are not possible because calculations for other flow conditions do not exist, so far.

From the previous discussions it is obvious that there are still some open questions left. Therefore, traces are not interpreted with respect to aerodynamic effects, so far. The comparisons provided to check the reliability of the signals may each for itself not be sufficient enough to favour the one or the other probe configuration. Nevertheless, what the author extracts from his tests is that it is necessary to be very careful if not suspicious when traces in high subsonic and supersonic flows are derived from a transducer with a normal screen.

5. Conclusion

From the tests described here it may be concluded that data from high-frequency-response pressure transducers are acquired and reduced satisfactorily. The method used is described in detail. The results are compared to outputs for transducers with and without a protective screen. To get information on which one might be the more reliable measurement device different cross-checks are used for comparison. Although there are still some open questions left it is suggested that for the measurement task described here the non-protected transducer is a better device than the protected one. An explanation which can be given is that the latter is too complicated a resonator for reliable tests. For the non-protected chip there are indications that problems occur if flow conditions are supersonic. This may be due to the corresponding shocks which may cause some kind of blockage in the vicinity of the sensing chip. Test will be continued with a single hole screen of 0.3 mm but are postponed until the promised new generation KULITE transducer which should be again more stable to temperature changes is available.

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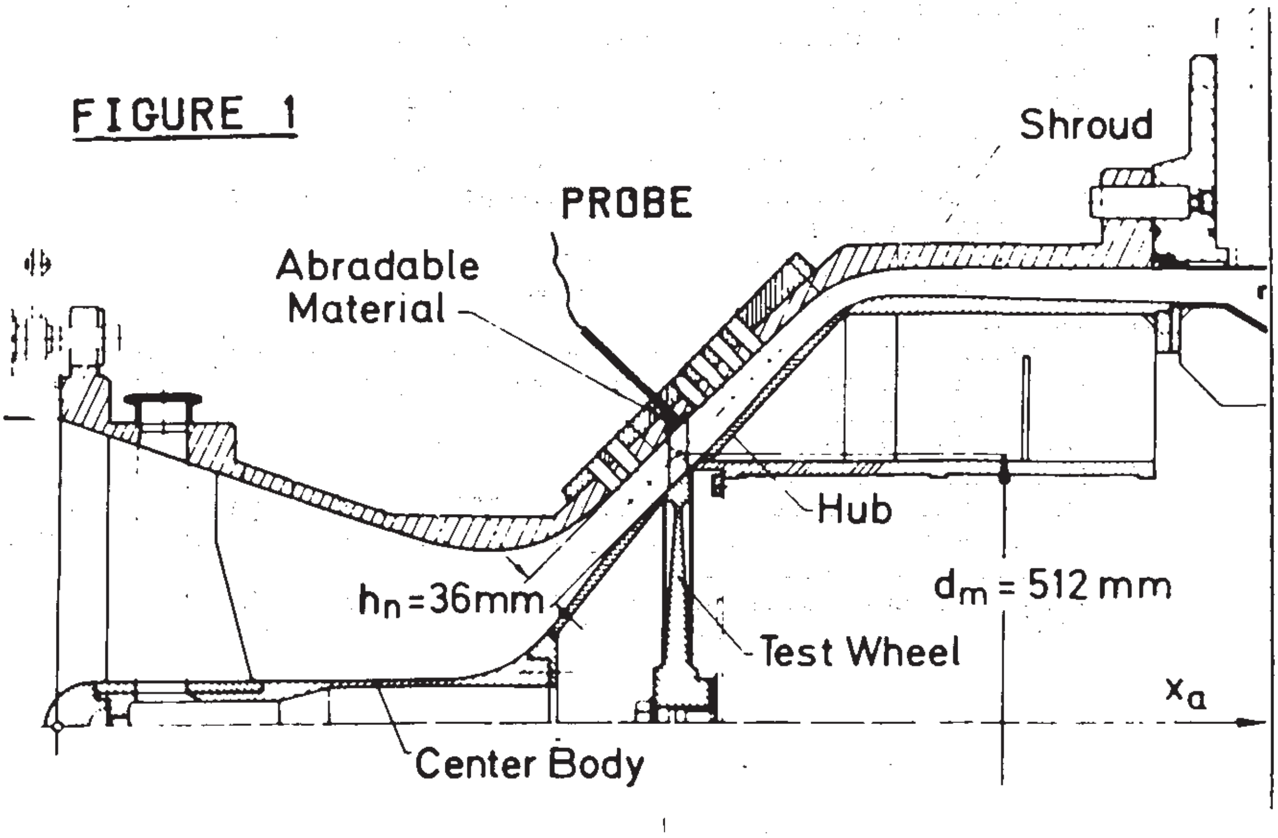
FIGURE 1



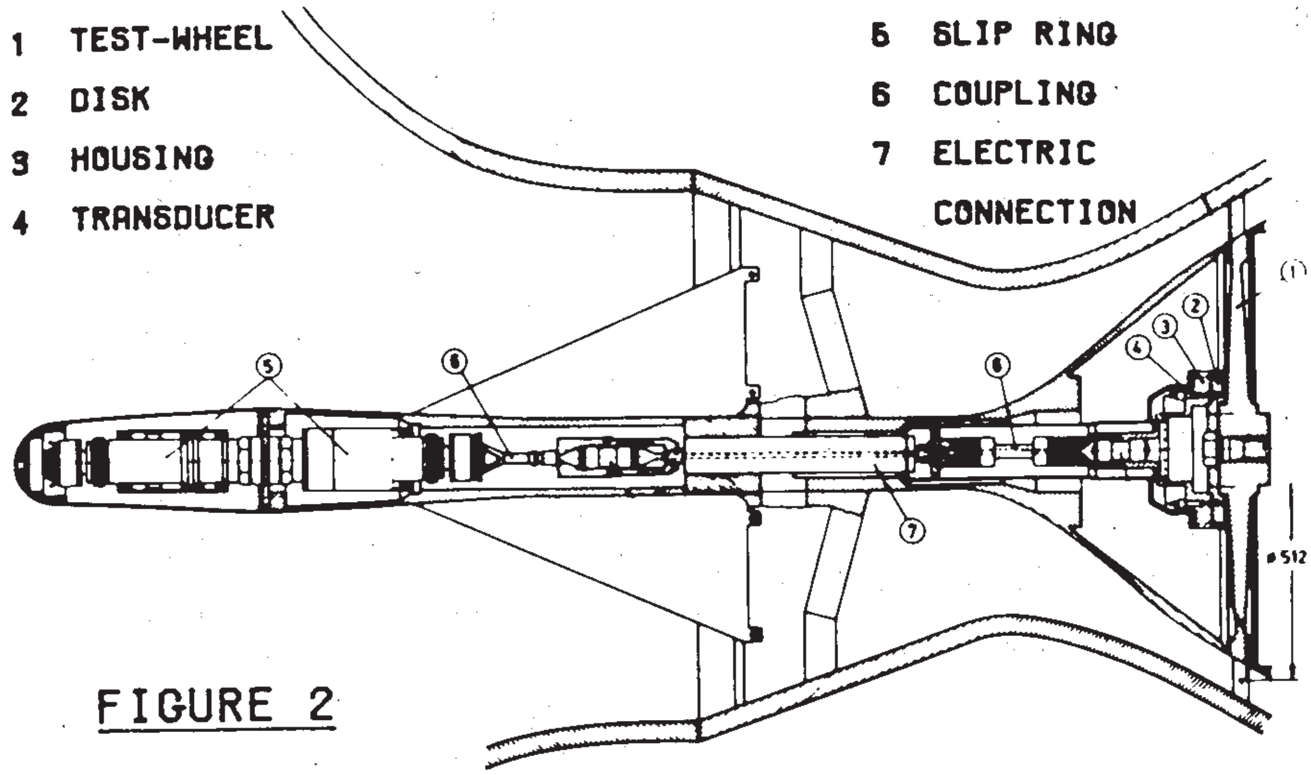


FIGURE 2

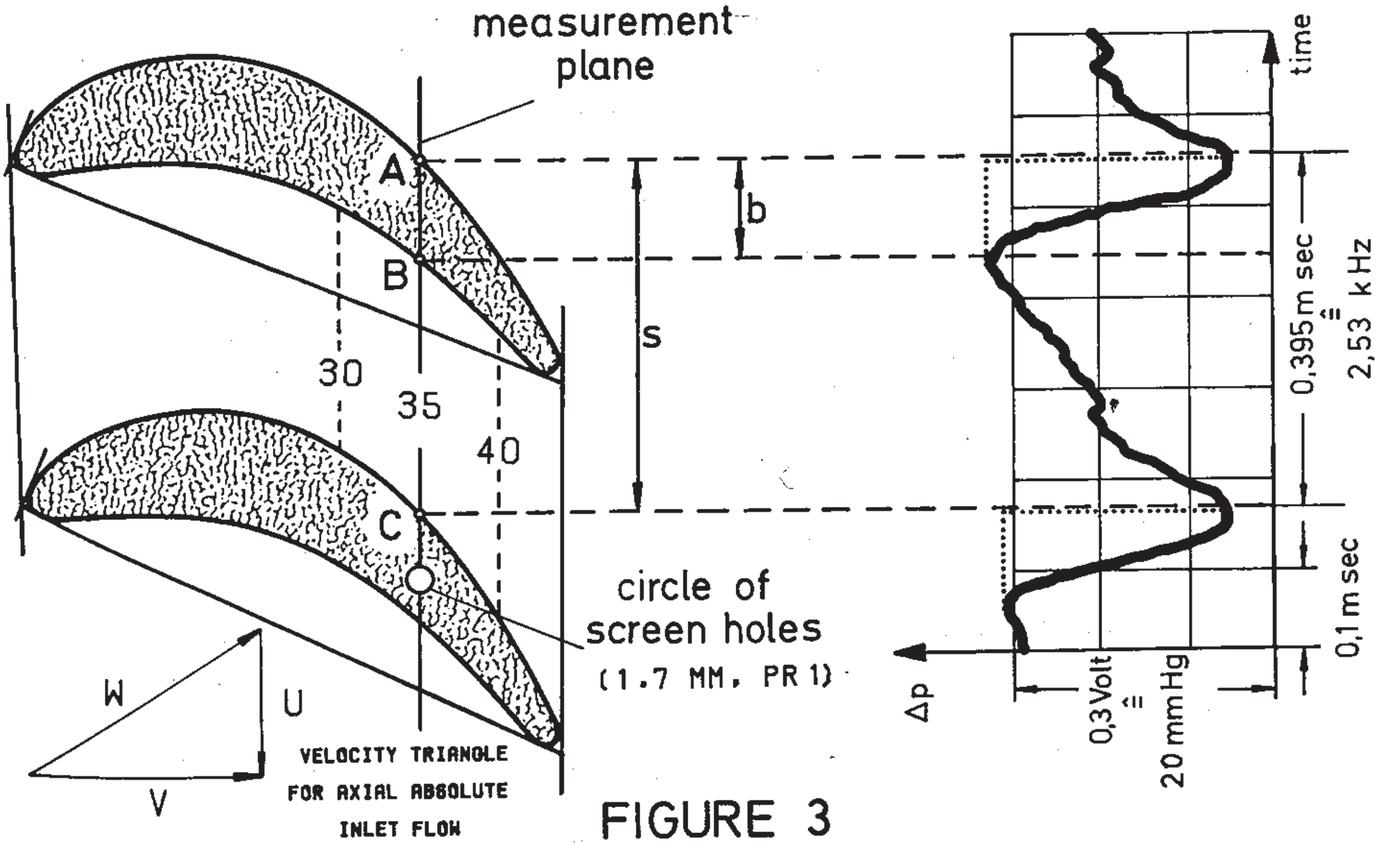
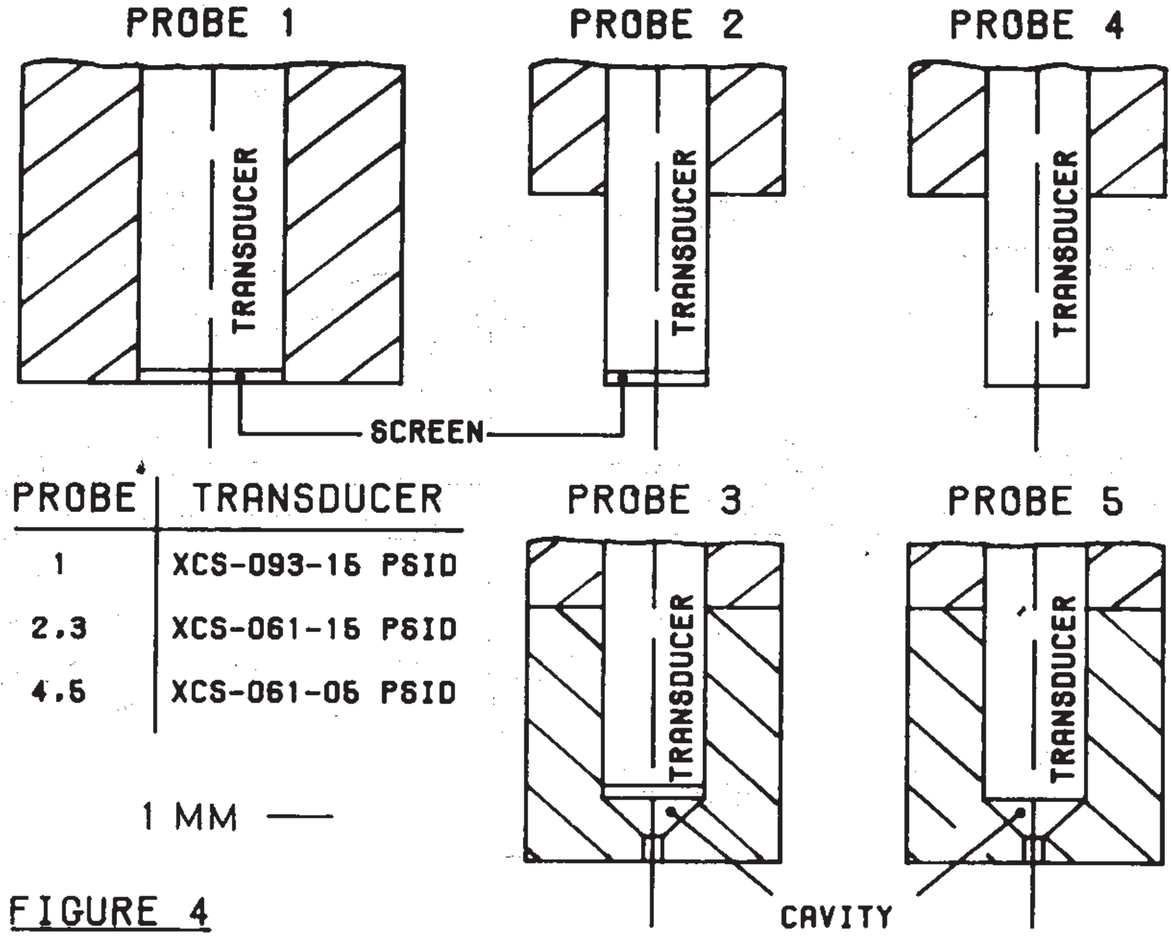


FIGURE 3



PROBE	TRANSDUCER
1	XCS-093-15 PSID
2,3	XCS-061-15 PSID
4,5	XCS-061-05 PSID

FIGURE 4

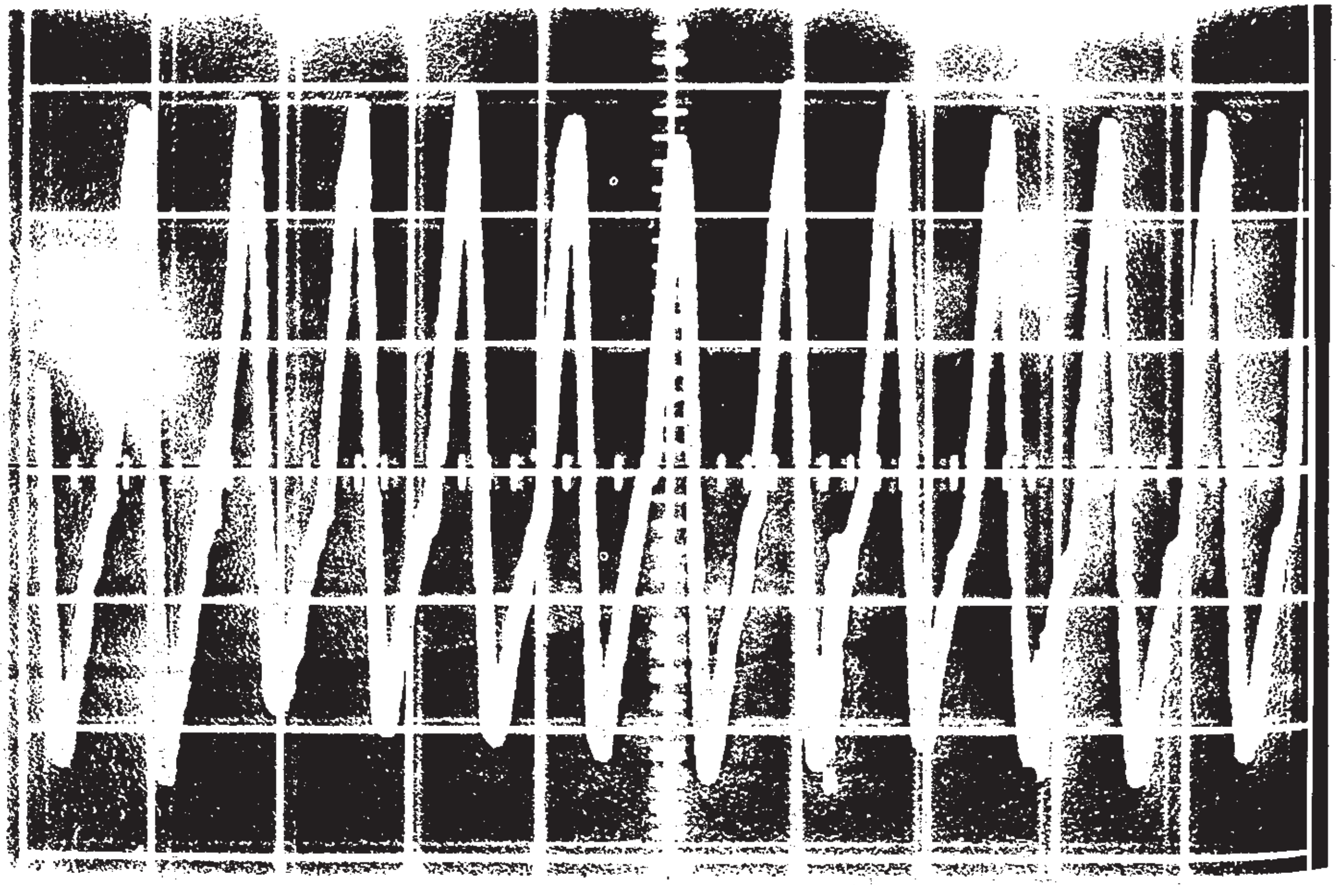


FIGURE 5

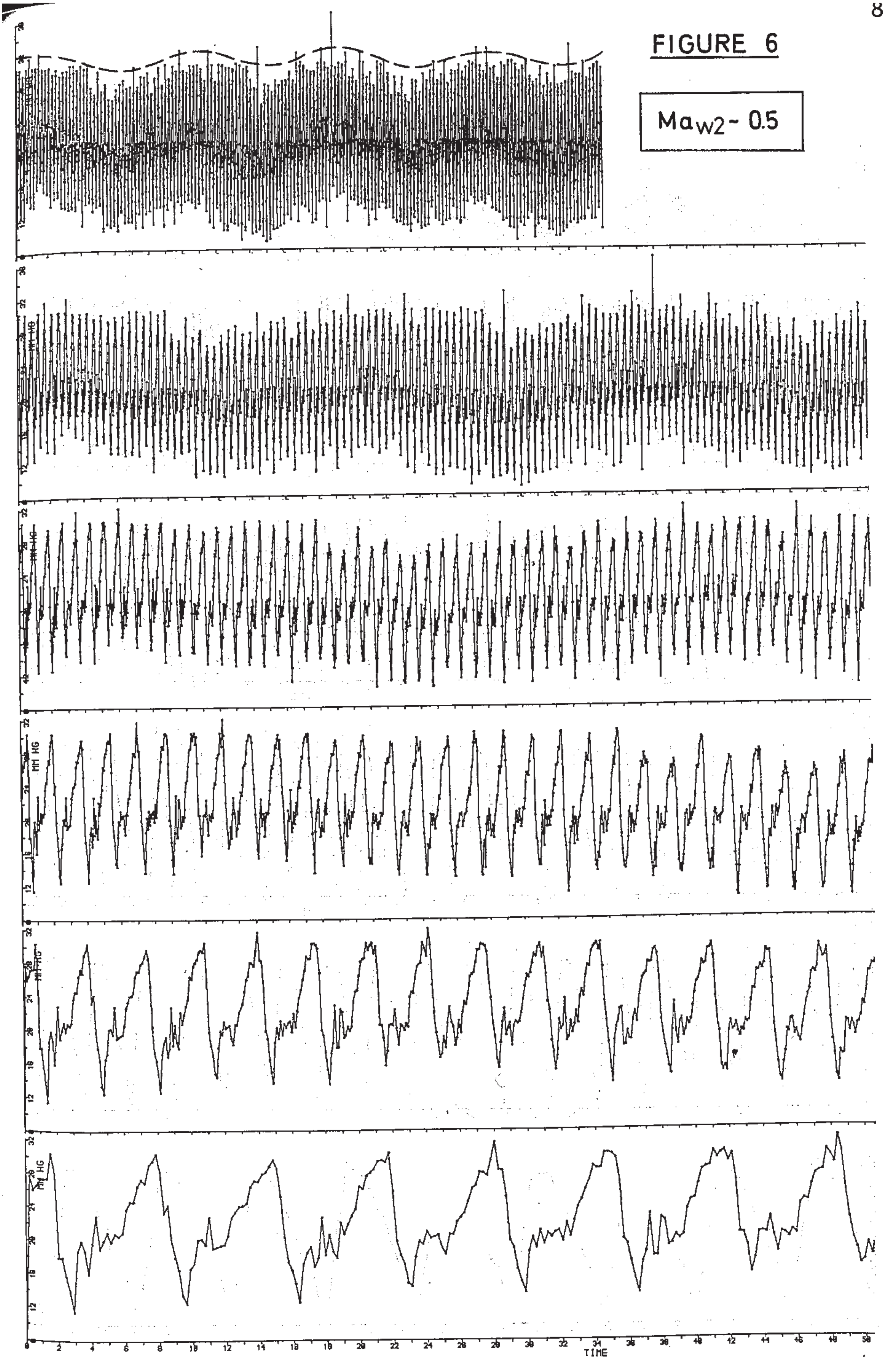


FIGURE 6

$Ma_{W2} \sim 0.5$

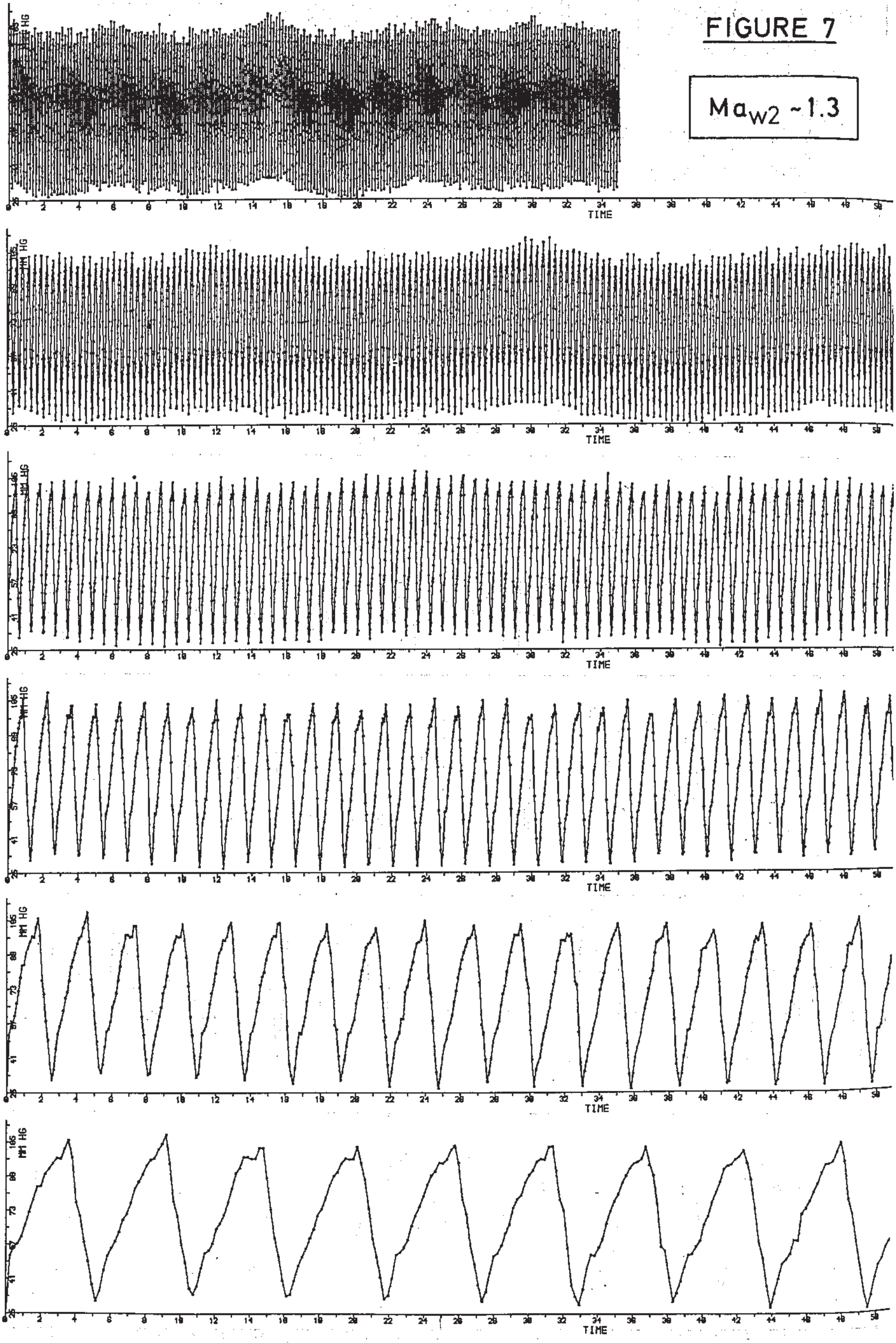


FIGURE 7

$Ma_{w2} \sim 1.3$

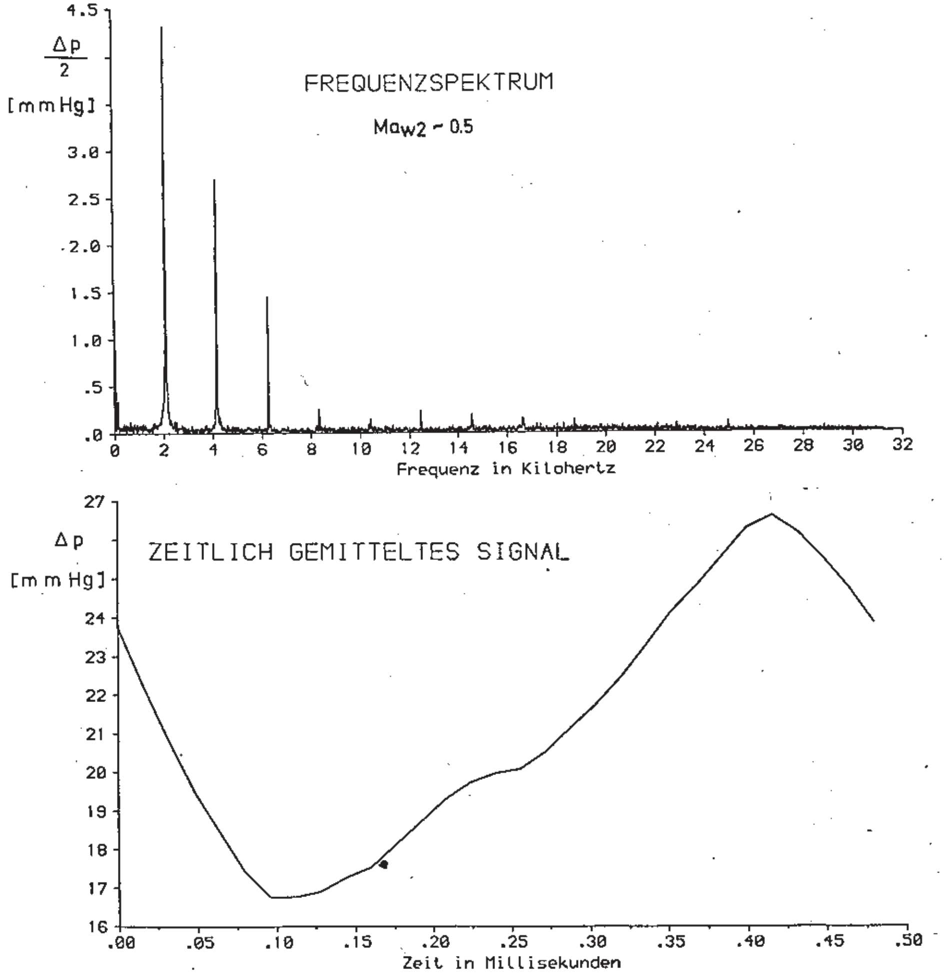


FIGURE 8

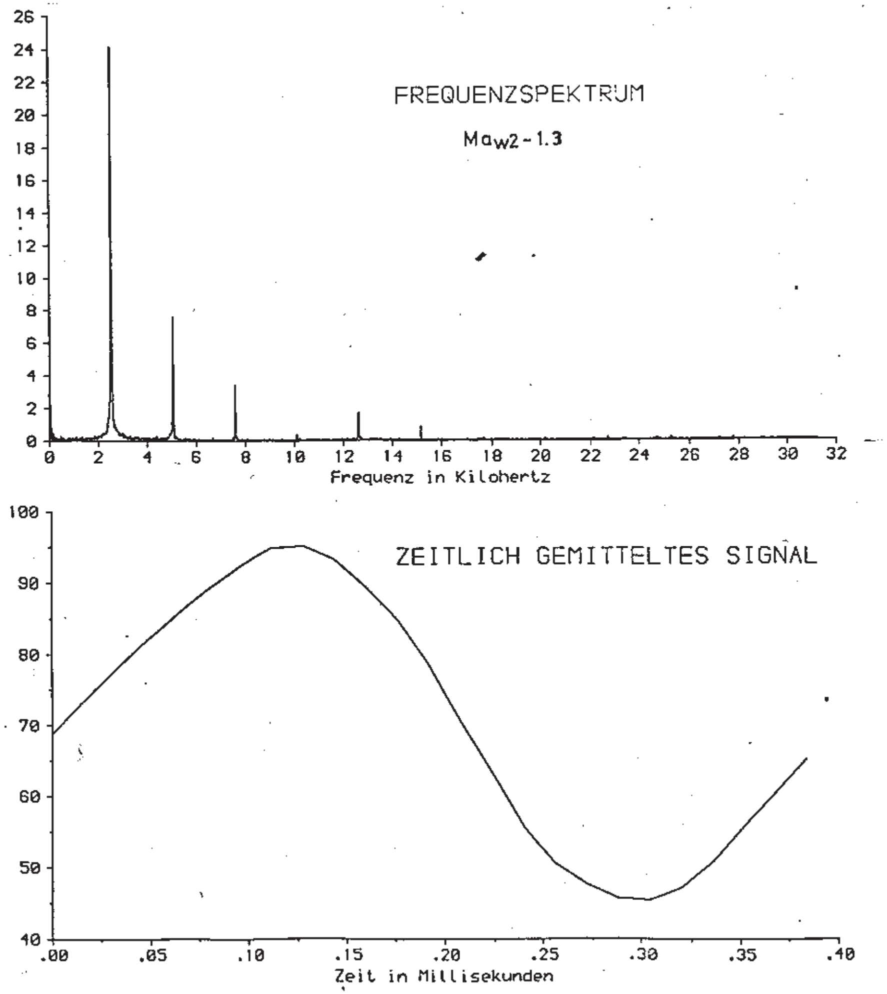
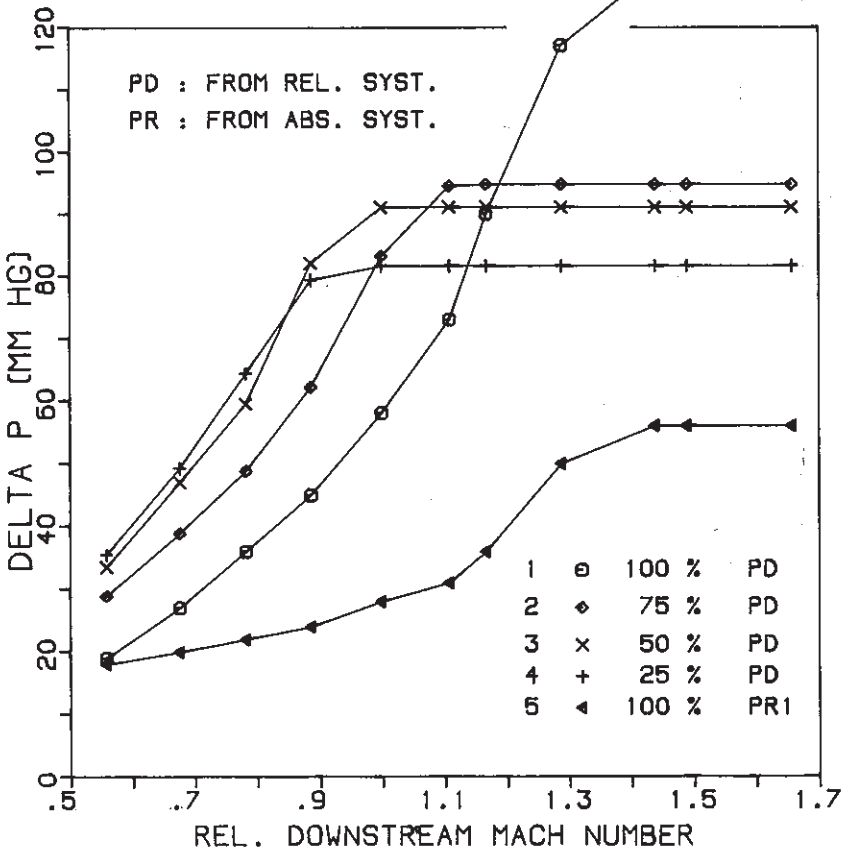


FIGURE 9

FIGURE 10



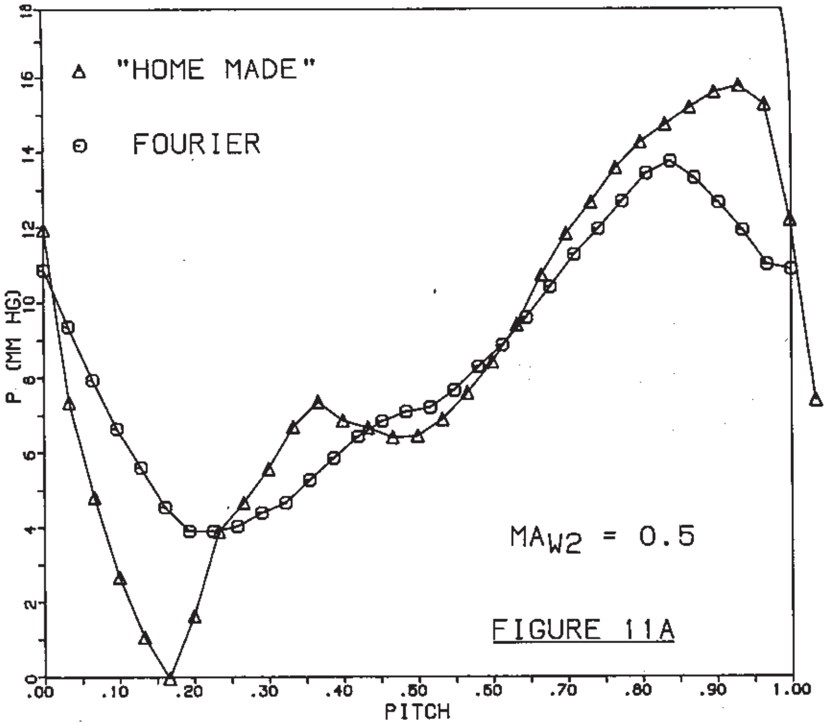


FIGURE 11A

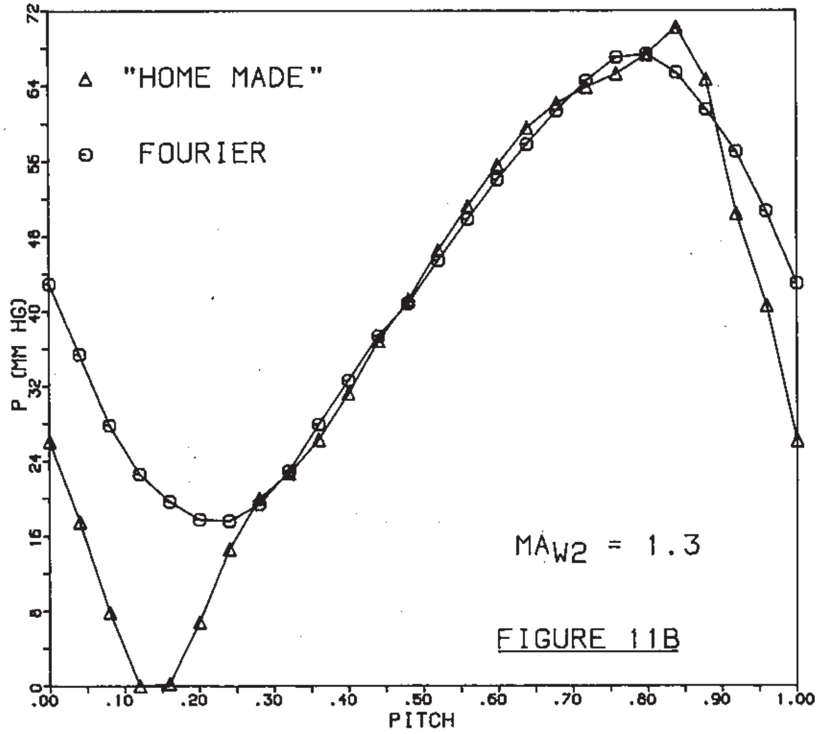
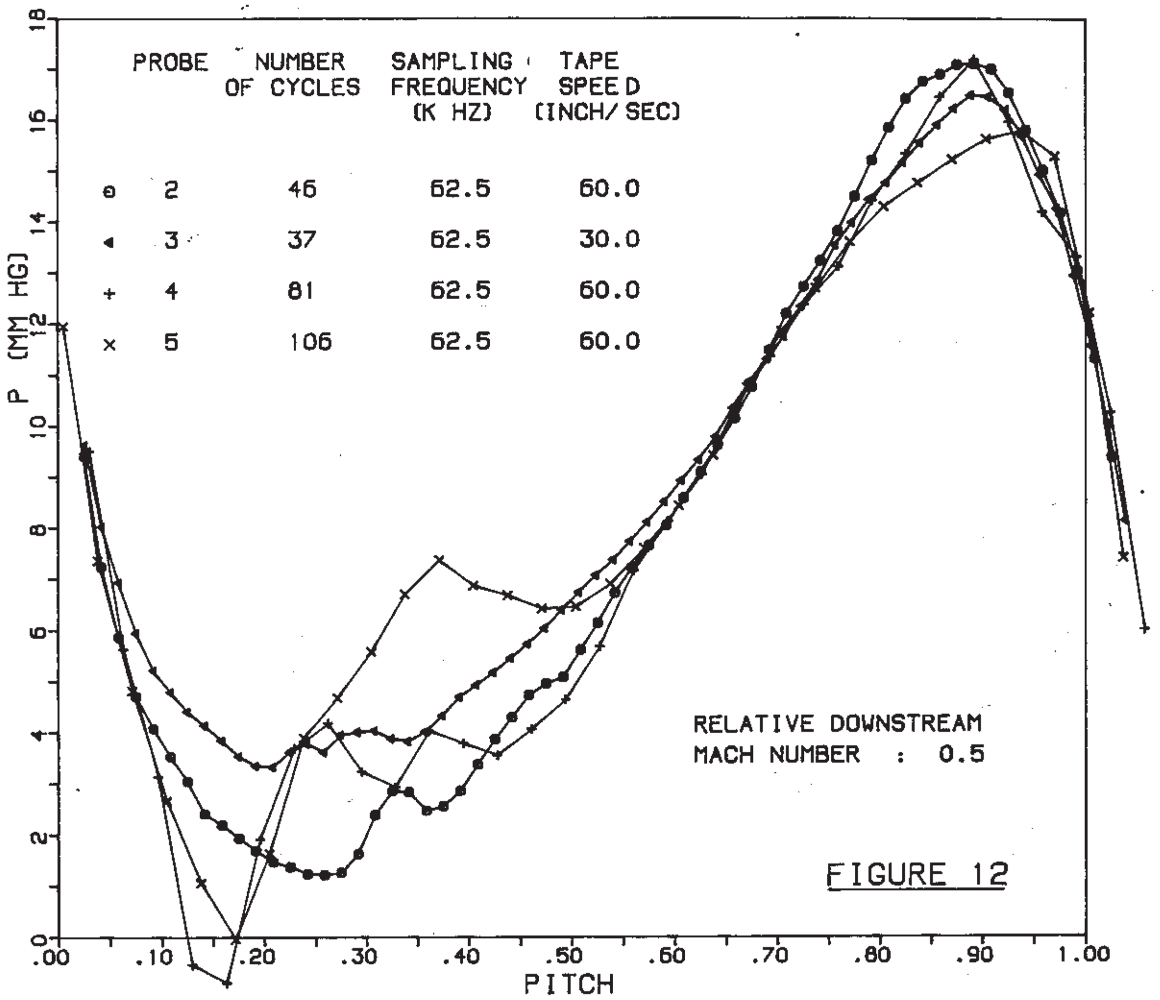
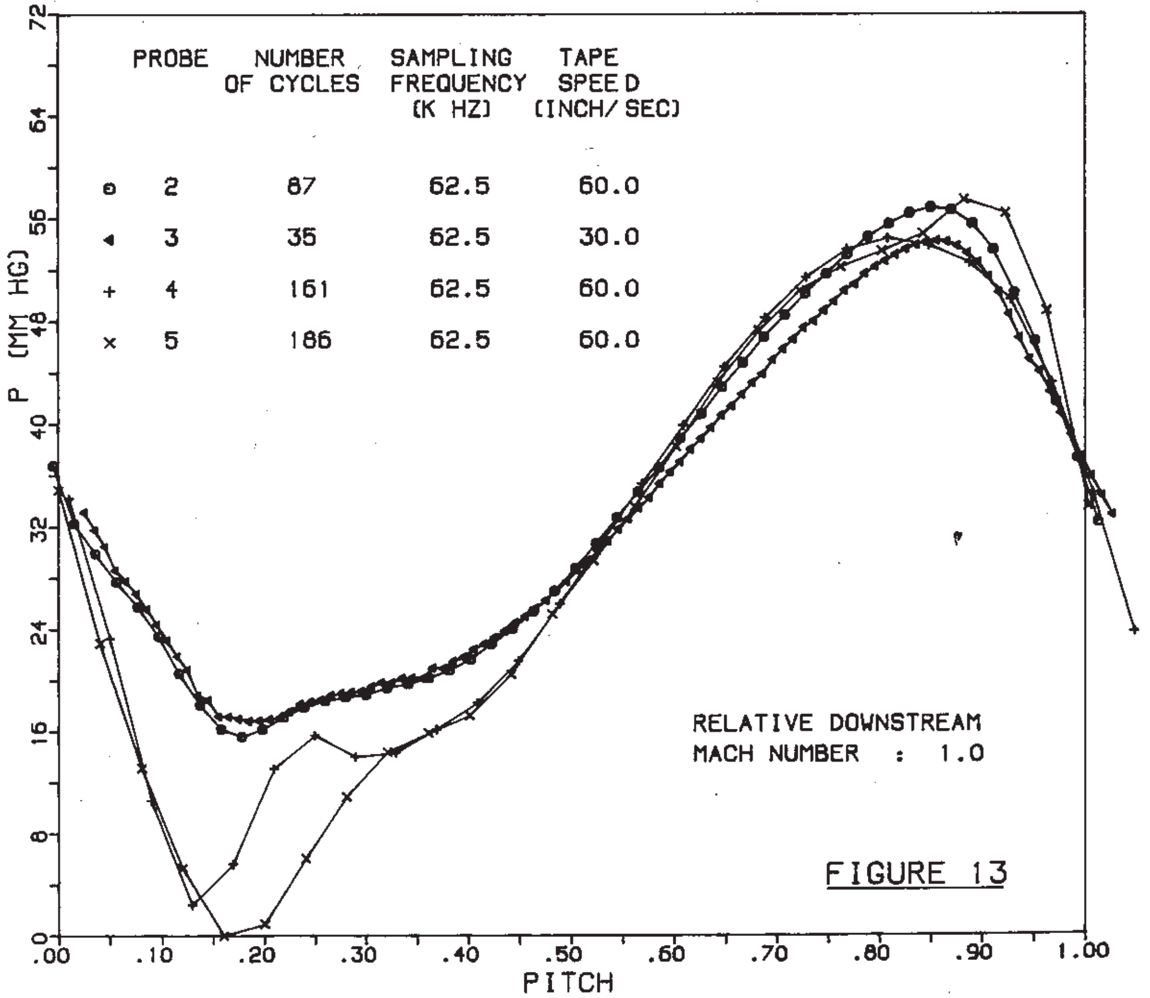


FIGURE 11B



RELATIVE DOWNSTREAM
MACH NUMBER : 0.5

FIGURE 12



RELATIVE DOWNSTREAM
MACH NUMBER : 1.0

FIGURE 13

FIGURE 14

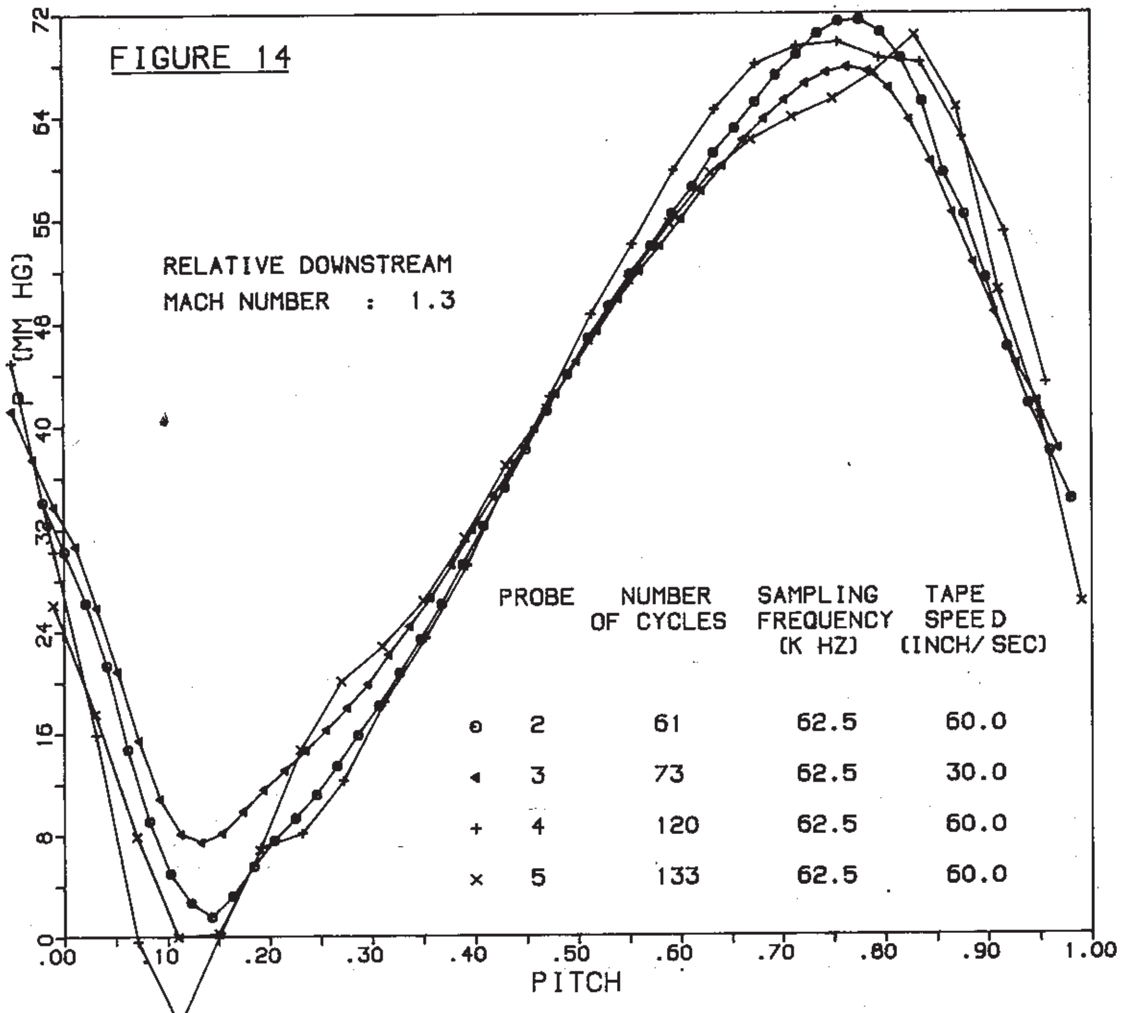


FIGURE 15

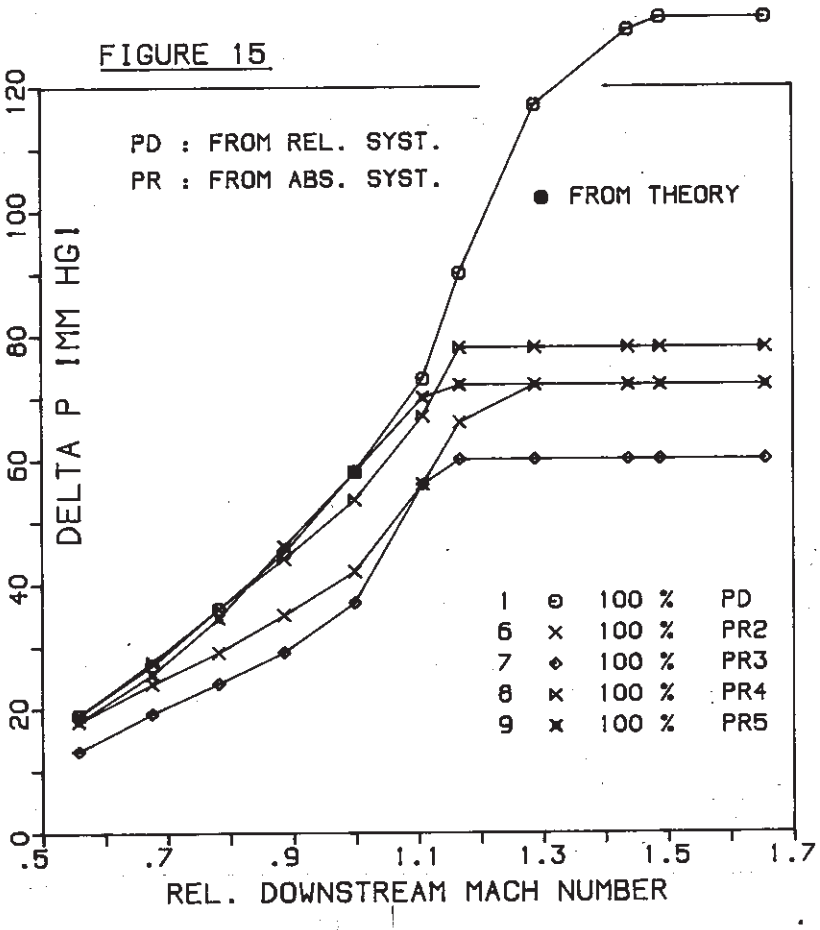
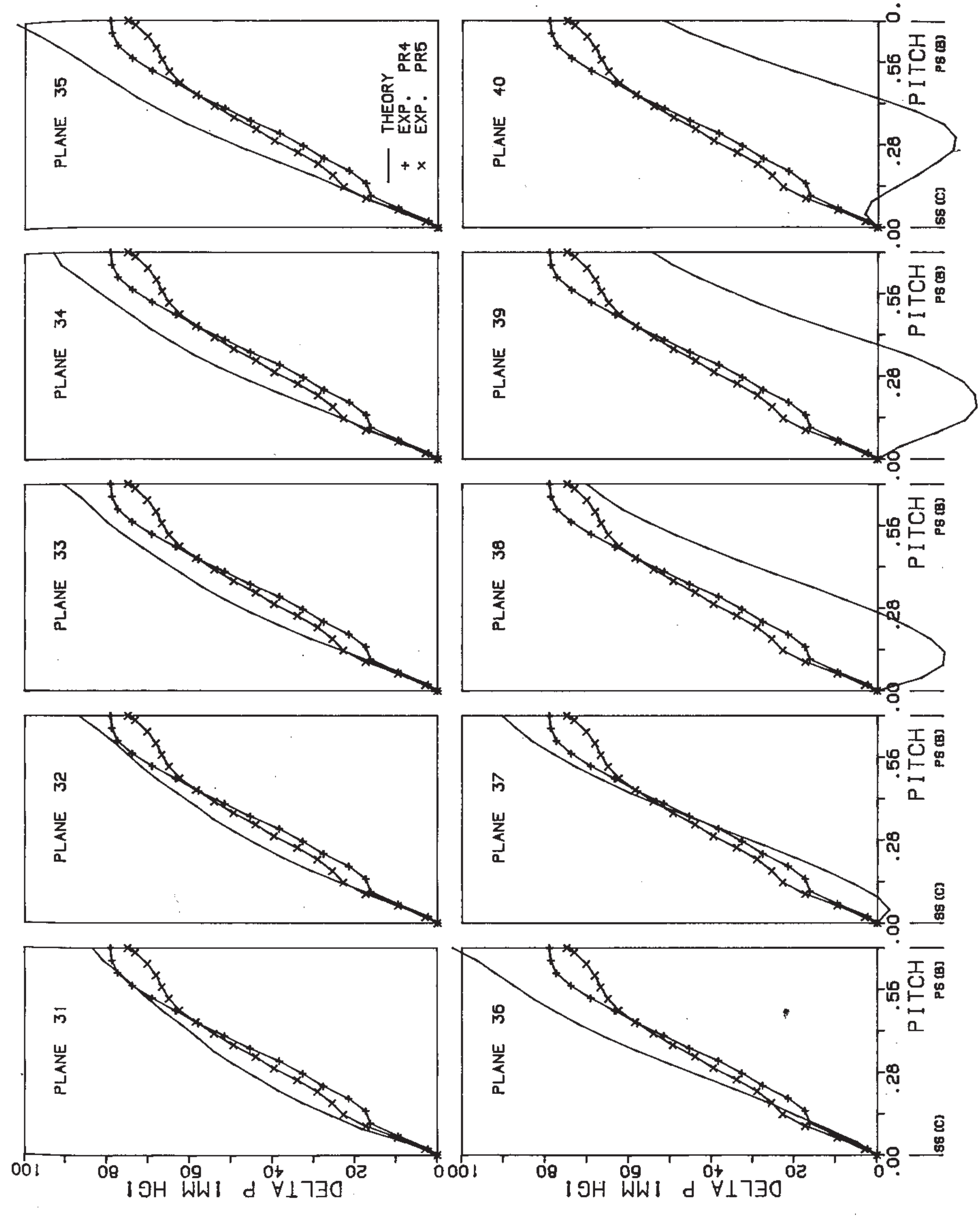


FIGURE 16


PLANE 31
PLANE 32
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PLANE 34
PLANE 35
PLANE 36
PLANE 37
PLANE 38
PLANE 39
PLANE 40
— THEORY
+ EXP. PR4
× EXP. PR5
DELTA P (MM HG)
0
20
40
60
80
100
.00
.28
.56
0.7
PITCH
SS (C)
PS (B)