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TRANSONIC CASCADE PERFORMANCE MEASUREMENTS USING A HIGH SPEED PROBE TRAVERSING MECHANISM IN A SHORT DURATION WIND TUNNEL

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Paper presented at the
9th Symposium on Measuring Techniques for
Transonic and Supersonic Flow in Cascades and Turbomachines
March 21-22, 1988, Oxford, UK

1. INTRODUCTION

The short duration, isentropic light piston compression tube cascade facility at the von Karman Institute provides full similarity with modern aero-engines with respect to Mach numbers and Reynolds numbers as well as freestream/wall/coolant temperature ratios. Although the tunnel originally was designed for convective heat transfer measurements only, it is evident that it would be also extremely attractive for aerodynamic performance measurements, if the measurement problems related to the short running time of ~400ms and the relatively high air temperature of 400 to 450°K could be overcome.

The probe traversing speed in the compression tube cascade tunnel must be of the order of 500 mm/s to cover a distance of 100 mm (~2 pitches) in 200 ms, compared to a traversing speed of only 1 mm/s in the conventional VKI cold flow high speed cascade facility, which is of the blow down type (air supply from high pression air reservoirs) with several minutes running time.

The probe-transducer-system response time is a function of the size of the transducer, the distance between probe head and transducer and the diameter of the connecting pressure tubes. Considering the desired traversing speed of ~500 mm/s and typical velocity gradients in the cascade outlet field a frequency response of 100 to 200 Hz was considered sufficient to obtain reliable performance measurements. It was estimated that at this relatively low frequency response, the transducer could be placed outside the test section avoiding not only transducer temperature sensitivity problems but also increased probe blockage effects due to increased dimensions of the probe head and/or probe shaft (depending on the position of the transducers).

The development of the performance measurement system for the compression tube cascade facility comprised four phases :

(1) testing of the frequency response of various probe-transducer systems;
(2) construction of a fast probe-traversing mechanism;
(3) Comparison of the performance measurements with the new fast probe-traversing system and a conventional low speed probe-traversing system in the cold flow blow-down cascade facility;
(4) performance measurements in the compression tube cascade facility and comparison with the results of the cold-flow blow-down cascade test rig.

2. TESTING OF FREQUENCY RESPONSE OF PROBE-TRANSDUCER-SYSTEMS

Two pressure transducers were extensively tested : a Kulite XCS-093 and a National Semiconductor LX 1620D, Fig. 1. Both transducers use piezoresistive integrated silicon sensor technology. The Kulite with its silicon sensing element mounted at the front of the transducer has a frequency response of several KHz even when used with a protective screen as in the present case. Because of its small diameter, it can be mounted in the probe shaft or even in the probe head.

The NS pressure transducer is quite different in construction. The various components - the pressure sensor chips, the amplifiers, the thick film resistors and the pressure connection tubes - are arranged side by side on a flat ceramique plate of about 19x21 mm^2. Its size does not allow it to be mounted into the probe shaft. There was no indication as to its frequency response, but it can be expected to be one order lower compared to the Kulite transducer.

The test procedure can be depicted from Fig. 2. The pressure transducers are connected via metal tubes of various lengths and diameters, simulating the probe, to a pressure jump generator, the main element of which is a fast acting cylindrical valve (5) separating a small cavity of volume V_1 from a large reservoir of volume V_2. After pressurization of V_2 and venting of V_1, the valve is actuated by a solenoid, thus connecting instantaneously volumes V_1 and V_2. Since the volume of the small cavity is negligably small compared that of the big reservoir, the pressure sensed by the probe is the same as the pressure in the reservoir before opening the valve.

The opening time of the valve and therewith the pressure rise time at the probe nose was checked with a Kulite pressure transducer flush mounted with the top surface of the cavity V_1. The oscilloscope trace in Fig. 3 indicates a pressure rise time of

~1 ms for a pressure jump of $\Delta P=200$ mm Hg. The pressure rise time for $\Delta P=50$ and 100 mm Hg was of the same order of magnitude.

Figure 4 shows the pressure response of both transducers for a pressure jump of $\Delta P=200$ mm Hg when connected to the pressure jump generator via a metal tube of 155 mm length and 1 mm inner diameter. Contrary to the flush mounted transducer the pressure rise is followed by more or less strong pressure oscillations around the imposed pressure value. Comparing the two tranducers it appears that the pressure rise for the NS transducer takes about 3 to 4 times longer than for the Kulite transducer, but the amplitude of the subsequent oscillations are much smaller. A decrease of the tube inner diameter from 1 mm to 0.8 mm does not seem to affect the response of the Kulite transducer but doubles the pressure rise time for the NS transducer, Fig. 5.

The main results concerning the effect of tube length and diameter are summarized in Fig. 6. The time t_1 (pressure rise time) is the time from the beginning of the pressure rise to the point where the recorded pressure reaches the pre-set pressure value. The time $t_2=t_1+\Delta t$ includes the time Δt needed to damp out the oscillations to a residual value of 2% of the pressure jump. In all cases, the response time of the Kulite transducer is significantly shorter than for the NS transducer.

The tests with a pressure tube length of 155 mm are the most interesting because, with a probe of this length, the pressure transducers can be positioned outside of the cascade test section, avoiding thus temperature problems. For this length and an internal diameter of d=1 mm, the response times and corresponding frequencies are :

	t_1	t_2	f_1	f_2
Kulite	1.7	9.5	588	105
NS	4	13.5	250	74

It is worthnoting that 90° bends in the metal tube with a bending radius of 5 mm did not affect the time response.

[For comparison we mention that the response time of a STATHAM pressure transducer, used under the same conditions as the NS and Kulite transducers, had a response time t_1 of ~60 ms].

Before deciding which transducer to use and which of the two time scales is the most important for probe traverses in the outlet field of transonic turbine cascades, it may be useful to discuss in more detail the type of pressure gradients the probes will encounter.

The gradients in the blade wake depend of course on the distance of the measurement plane with respect to the trailing edge plane, but the wake width typically extends over 1/3 to 2/3 of the pitch, i.e. for a cascade with a pitch of 60 mm the half-wake width covers about 10 to 20 mm. This corresponds to a probe displacement time of 20 to 40 ms for a probe traversing speed of 500 mm/s. This is 5 to 8 times the pressure rise time t_1 if the probe is connected to a NS transducer and 12 to 25 times that of the Kulite transducer. Under these conditions pressure oscillations are not at all expected to occur.

Contrary to wakes, shocks present pressure discontinuities. However, the interference of the probe nose with the shock front smears out the pressure jump over a distance approximately equal to the outer diameter of the probe head i.e. 2,5% of the pitch in the present case, corresponding to 3 ms probe travel time. This is still twice as long as the pressure rise time t_1 of the probe connected to the Kulite transducer. The smearing of the pressure rise through the shock due to the shock-probe interference has a secondary effect; namely the oscillations will be certainly less than those in Fig. 4.

The situation is somewhat less favorable for the NS transducer since its pressure rise time t_1 of 4 ms is longer than the probe travel time of 3 ms needed to traverse the shock. This will lead to a further smearing of the shock but even in this case it is expected that the measured pressure rise will not occupy more than 5% of the pitch. The error due to the smearing of the pressure jump as well as the errors due to any subsistant subsequent pressure oscillations, which are certainly smaller than the maximum amplitude of 10% obtained with the a pressure jump generator (see Fig. 4b), are only of local importance. Averaging over the pitch should make their contribution to the total cascade losses negligably small.

From the above considerations it appears that the NS pressure transducer meets all technical requirements for performing reliable cascade measurements with a high speed probe traversing mechanism. The transducer can be placed sufficiently far from the probe head to connect it outside of the test section to the probe thus avoiding any temperature problems. The cost of an NS transducer is only a small fraction of that of a Kulite transducer.

3. HIGH SPEED PROBE TRAVERSING MECHANISM

The conventional VKI probe carriage used in the cold flow blow down cascade test rig is driven by an electric DC motor allowing a maximum probe displacement speed of 5 mm/s. However, normal traversing speed is only about 1 mm/s because of the slow response of the STATHAM pressure transducers used with this carriage. The corresponding probe is a two-finger probe with a combined total- directional probe head and a separate cone probe for the static pressure.

A picture of the new high speed probe carriage is presented in Fig. 7. The carriage is driven by a pneumatic piston. The traversing speed is controlled by the air supply pressure and throttle valves for the air bleeds. The displacement is measured by a linear variable differential transducer. The maximum displacement speed is ~ 800 mm/s. The probe used with this carriage was exactly the same as the one for the low speed carriage except for the absence of the cone probe head for the static pressure, which was taken instead from side wall pressure tappings. For simplicity and in view of the exploratory character of these tests, it was not attempted to measure the flow angle. Hence the loss data are presented only in the form of area-averaged values.

With a maximum tube length between probe head and transducer of 155 mm, as used in the calibration tests, the transducer had to be attached to the probe shaft. This proved to be very impractical and finally it was decided to attach it to the wall of the carriage housing, although this implied an increase of the pressure transmission line of 100 mm. For the tests in the compression tube cascade test rig the minimum required distance between probe head and transducer turned out to be even longer - about 400 mm - in order to place the transducer outside of the outside housing to avoid slight zero-drifts due to the momentary temperature rise in the carriage housing.

4. PERFORMANCE MEASUREMENTS

The cascade consists of 5 high-turning nozzle guide vanes, Fig. 8. The blades are made of aluminium. The downstream measurement plane is situated at a distance $X/Ca_x=0.32$ from the trailing edge plane. The cascade is tested in the Mach number range $0.9 \leq M_2 \leq 1.15$.

4.1. Cold flow blow down cascade test rig

Figure 9 shows the raw total pressure traces at outlet Mach numbers $M_2=0.9$ and 1.1 obtained with the fast traversing probe at probe displacement speeds of 780, 110 and 30 mm/s. The different degree of unsteadiness in the traces is due to different acquisition times per sample unit. It is by no means representative of the turbulent character of the flow. After smoothing, the curves differ very little from each other inspite of the wide range of the probe speeds, Fig. 10. However one observes that the pressure rise through the shock for the test at $M_2=1.1$ is slightly affected by the probe speed. The area-averaged losses are plotted in Fig. 11 as a function of the traversing speed. The figure shows a slight scatter of the data but no clear trend of the losses with the probe displacement speed. The scatter is of the same order of magnitude as that observed for repeat tests at the same speed. We may therefore conclude that the distance of 250 mm between probe tip and transducer is still adequate to perform reliable measurements at high traversing speeds.

The losses at 780 mm/s probe displacement speed are compared in Fig. 12 with those measured with the conventional low speed probe traversing system at ~ 1 mm/s. The agreement is very good.

4.2. Compression tube cascade facility

The test section is identical with that described in 4.1. except for the central blade which is replaced by a ceramic blade. The surface finish of this blade is better than that of the other aluminium blades.

When mounting the high speed probe carriage onto the compression tube test chamber it turned out that for reasons related to the particular construction of the test chamber the length between probe tip and transducer had to be increased to 400 mm. Unfortunately there was no time left to investigate systematically the effect of traversing speed for this tube length. The tests were done with a probe speed of 500 mm/s. The validity of these tests is to be juged on the ground of comparisons with the data from the cold flow blow down tunnel.

Figure 13 shows a typical downstream absolute total pressure trace at M_2=0.9. The right wake corresponds to the central blade. The apparent smoothness of the wake trace is mainly due to the increased damping through the longer probe tip - transducer distance (400 mm instead of 250 mm in the cold flow blow down tunnel).

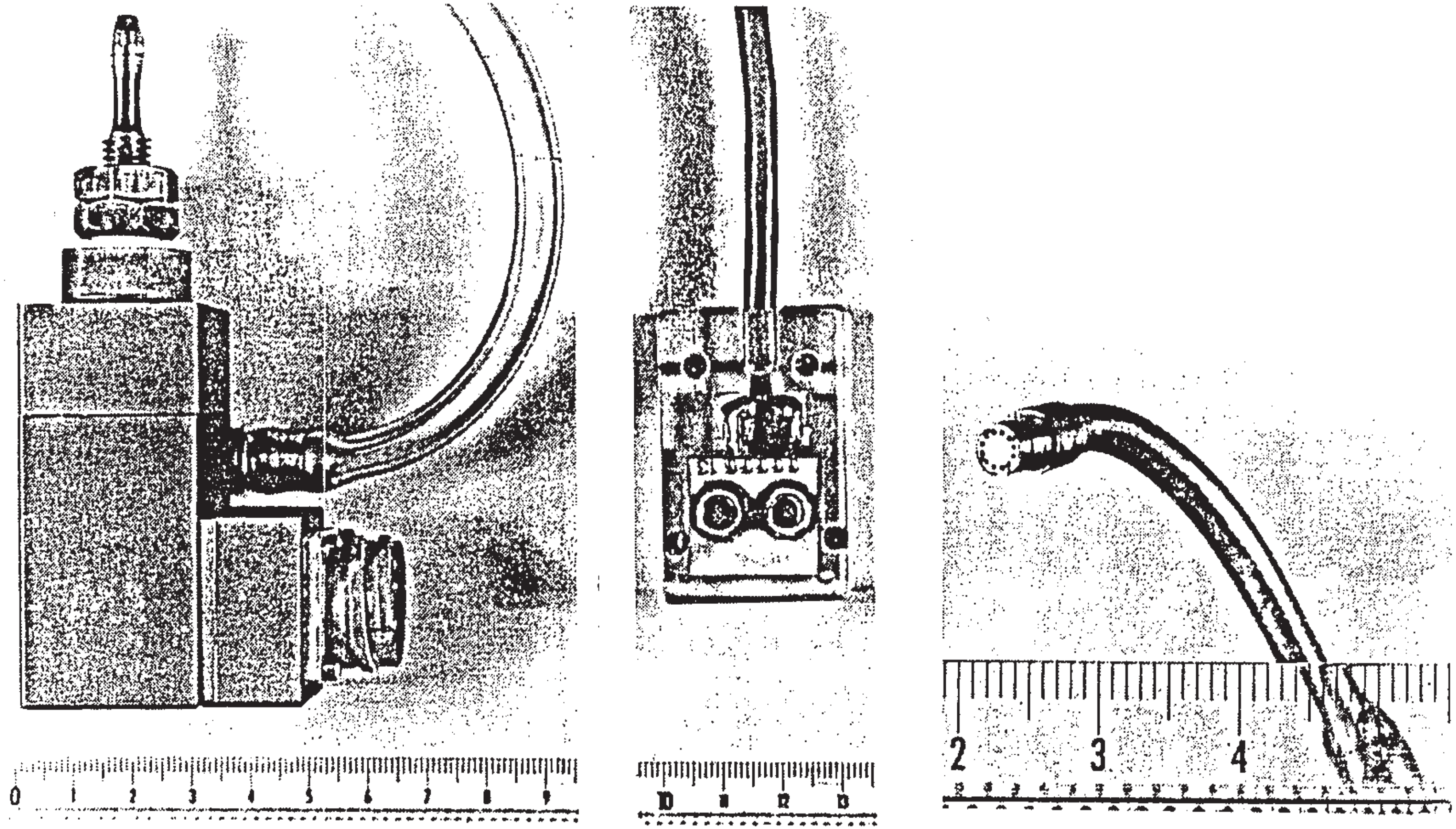
Low frequency pressure oscillations of 10 to 20 Hz with amplitudes of 1 to 3% of the total pressure are a commun feature of all compression tube cascade tunnels. These pressure fluctuations are also present in the total pressure trace in Fig. 13 although they are not clearly visible because of the presence of the wakes.

In conventional blow down cascade facilities with constant total upstream pressure it is common practice to evaluate the total pressure losses by measuring the differential pressure between the upstream settling chamber and the downstream probe. In the presence of overall pressure fluctuations as in the compression tube facility it is vital (a) to minimize the physical distance between the probes positioned upstream and downstream of the cascade and (b) to ensure that the response times for both transducers are the same. The solution retained for the present case was to position the upstream probe at ~ 1 chord length from the cascade leading edge and at 25% of the blade height from the side wall to avoid any effect of the probe wake on the cascade mid-span flow.

The losses measured in the compression tube facility are added in Fig. 12 to those obtained in the cold-flow blow-down tunnel. The losses of the compression tube cascade are slightly lower, possibly because of the smaller surface roughness of the ceramic blade. This point requires further investigation. Also further tests are planned to prove the adequacy of the probe-transducer-system response time for a tube length of 400 mm.

ACKNOWLEDGEMENTS

The authors would like to thank MM. Bry and Klinger of SNECMA for having stimulated this project and for their useful comments throughout the work.

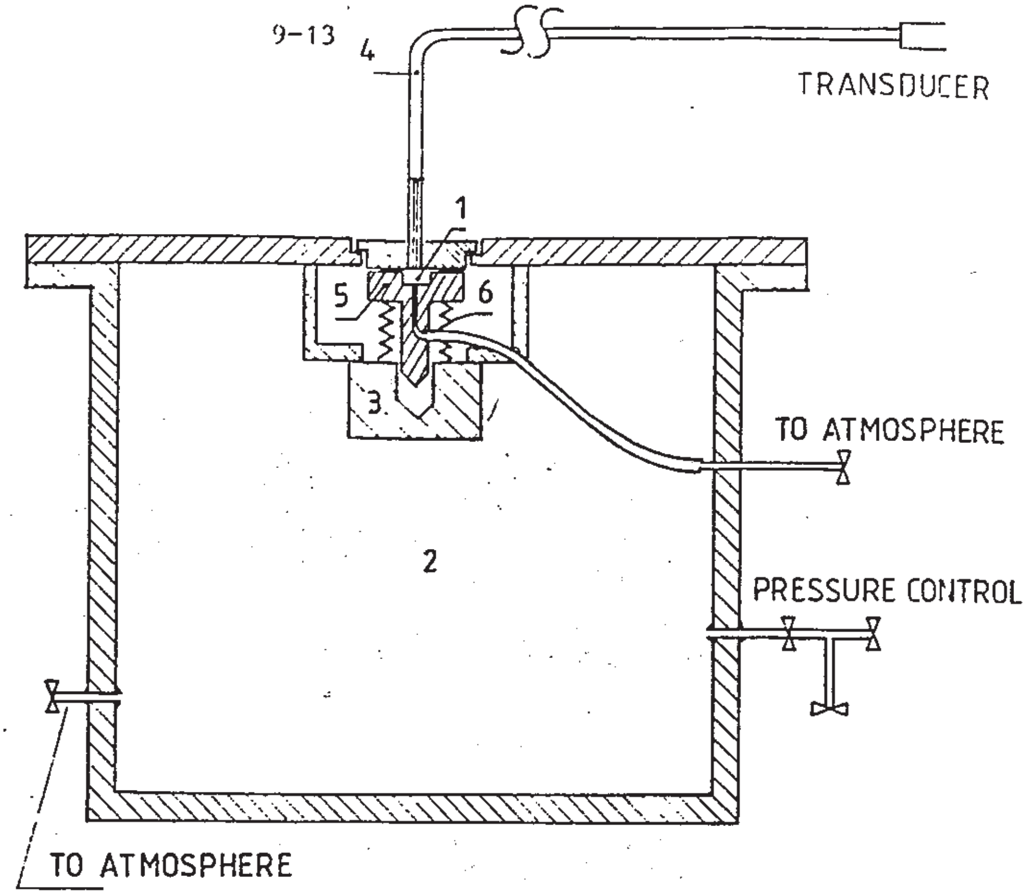


STATHAM

NATIONAL
SEMI CONDUCTEUR

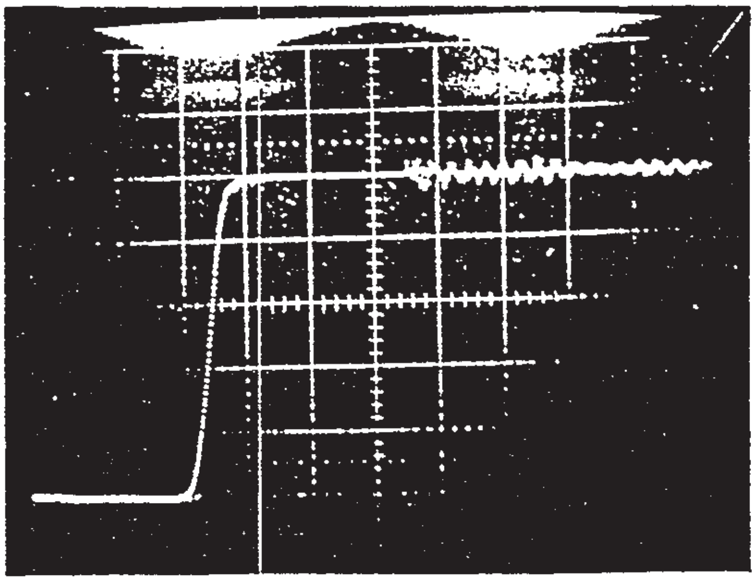
KULITE

FIG. 1 - PRESSURE TRANSDUCER



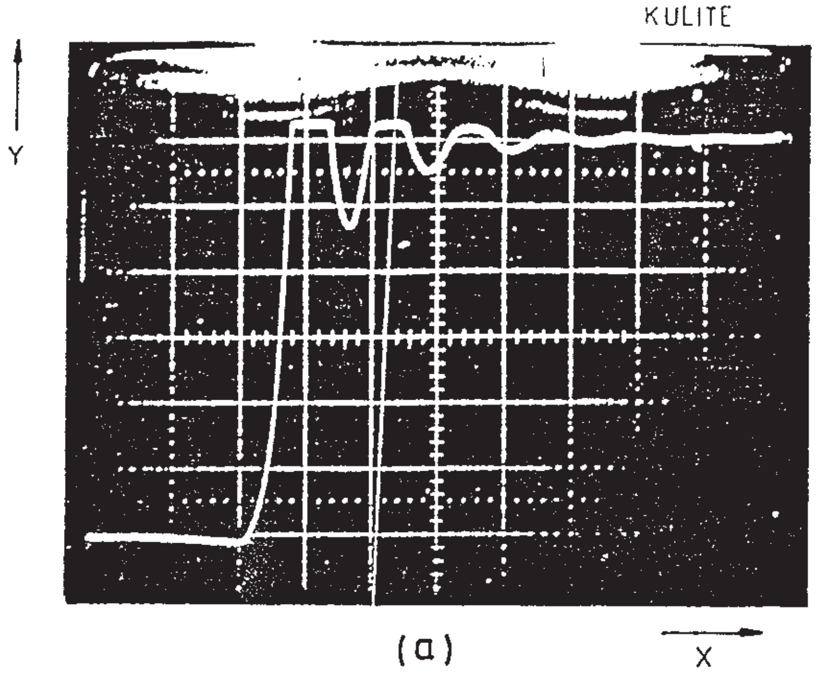
1 - SMALL CAVITY OF VOLUME V_1
2 - RESERVOIR OF VOLUME V_2
3 - SOLENOÏD : S
4 - TUBE CONNECTING CAVITY V_1 WITH TRANSDUCER
5 - VALVE

FIG. 2 - PRESSURE JUMP GENERATOR



Δp = 200 mm Hg
X : 2 m/s / grad.
Y : 1 V / grad

FIG. 3 - PRESSURE RISE TIME IN CAVITY V_1



TUBE l = 155 mm

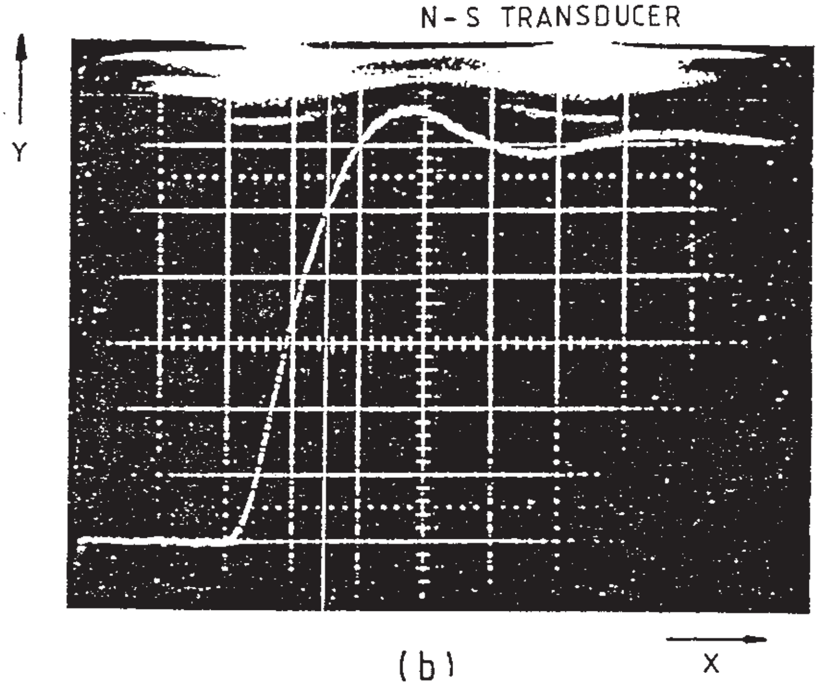
ϕ_{INT} = 1 mm

ΔP = 200 mm Hg $\overset{\wedge}{\longrightarrow}$ 6V

X : 2 ms / GRAD

Y : 1V / GRAD

(a)



TUBE l = 155 mm

ϕ_{INT} = 1 mm

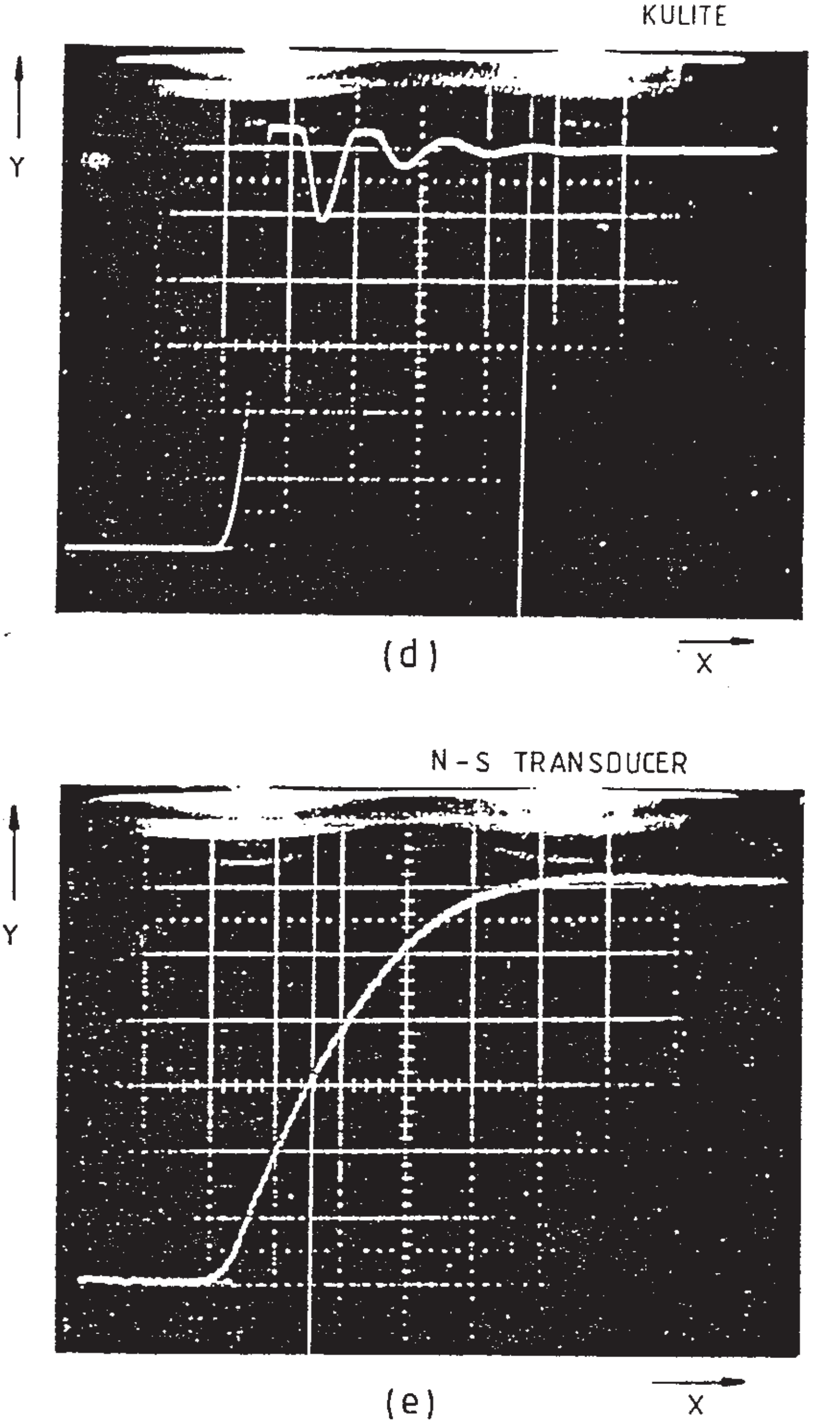
ΔP = 200 mm Hg $\overset{\wedge}{\longrightarrow}$ 0.3

X : 2 ms / GRAD

Y : 1V / GRAD

(b)

FIG. 4 - PRESSURE RESPONSE CURVES FOR KULITE (a)
AND N-S (b) TRANSDUCERS.
Tube length l = 155 mm , diameter d = 1 mm



KULITE

TUBE l = 155 mm
ϕ_{INT} = 0.8 mm
ΔP = 200 mm Hg $\overset{\wedge}{\longrightarrow}$ 6 V
X : 2 ms / GRAD
Y : 50 V / GRAD

(d)

N - S TRANSDUCER

TUBE l = 155 mm
ϕ_{INT} = 0.8 mm
ΔP = 200 mm Hg $\overset{\wedge}{\longrightarrow}$ 0.3
X : 2 ms / GRAD
Y : 50 V / GRAD

(e)

FIG. 5 - PRESSURE RESPONSE CURVES FOR KULITE (a) AND N-S (b) TRANSDUCERS.
Tube length l = 155, diameter d = 0.8 mm

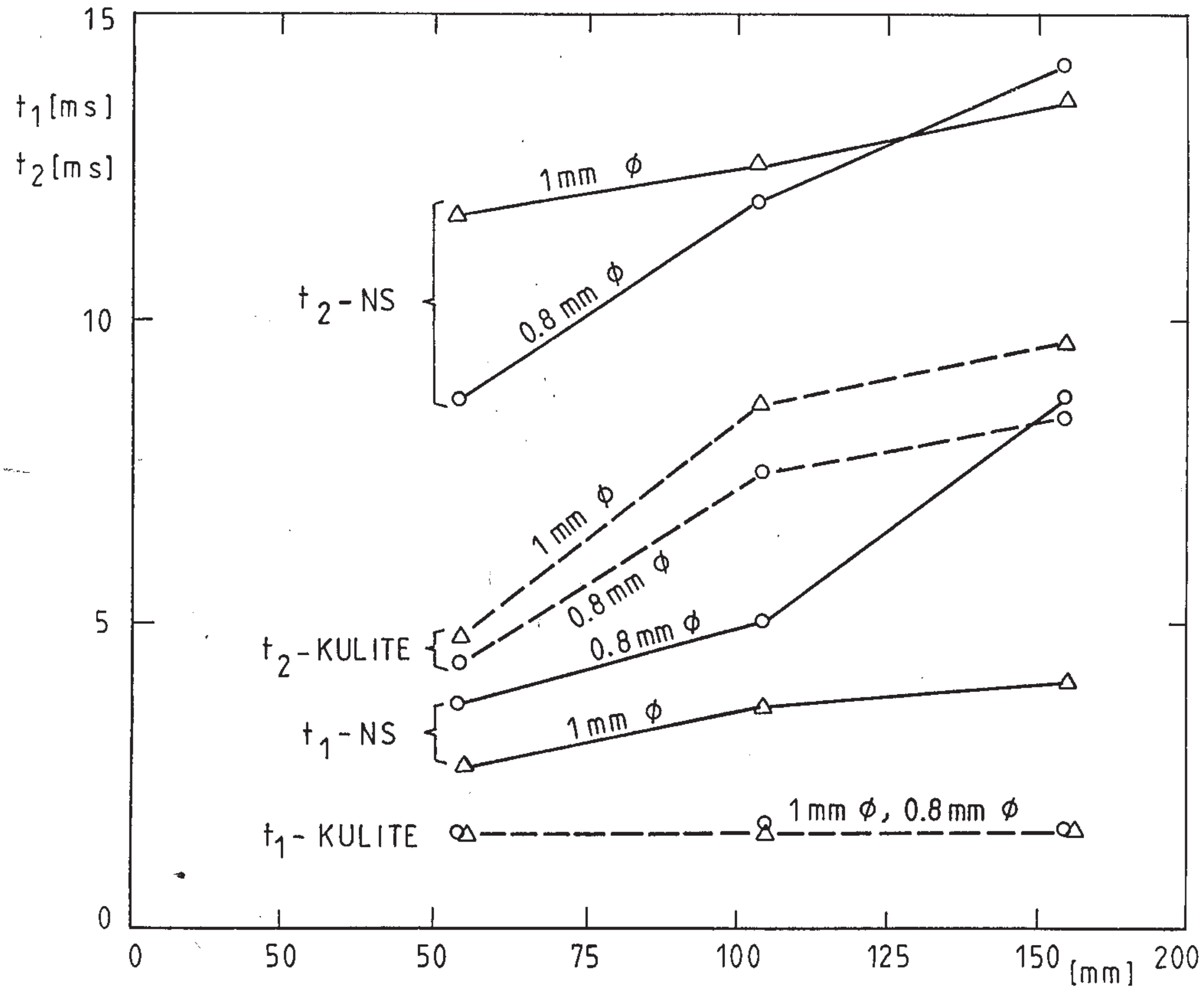


FIG 6 - EFFECT OF TUBE LENGTH ON TRANSDUCER RESPONSE TIME

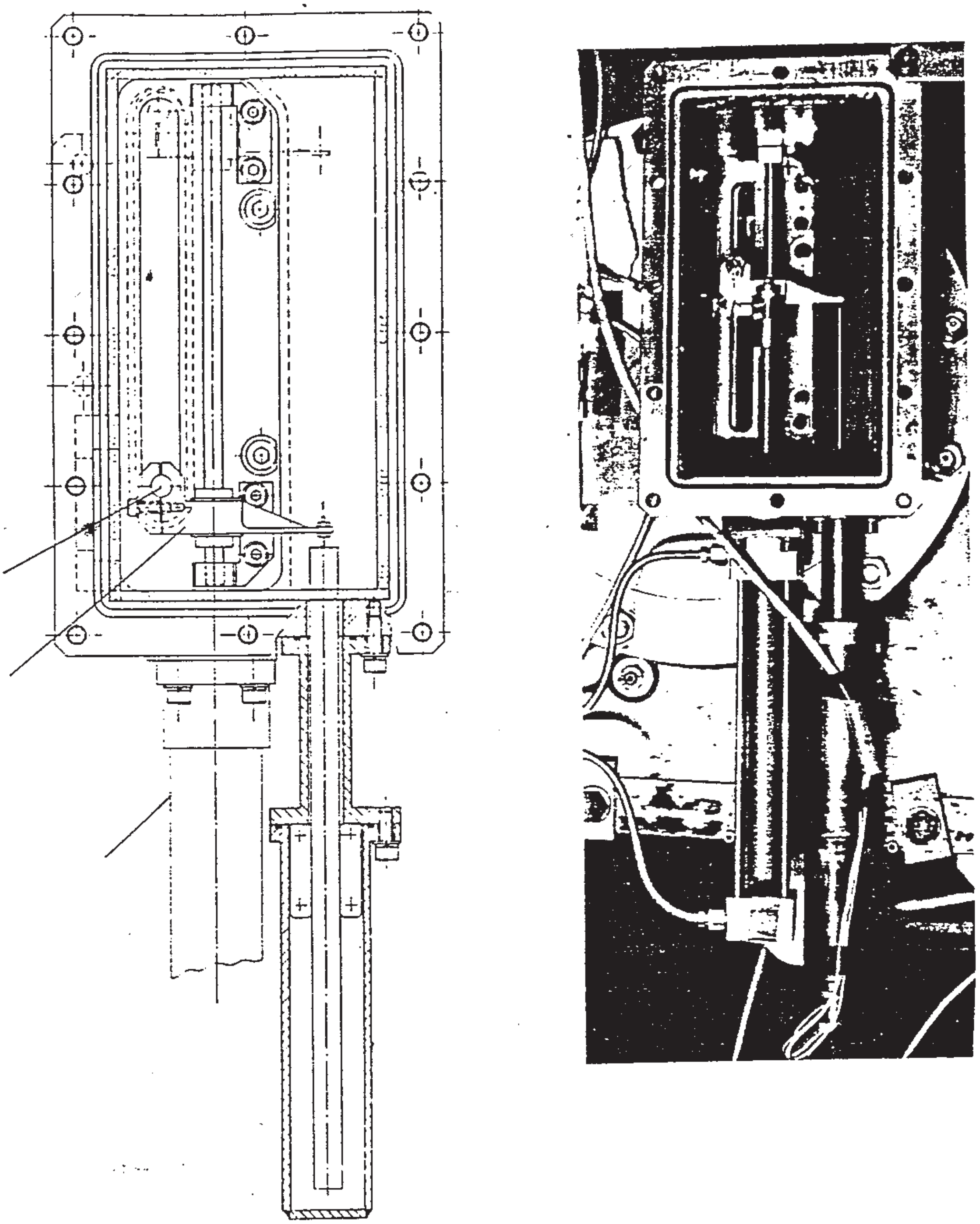


FIG. 7 - HIGH SPEED PROBE TRANSVERSING MECHANISM

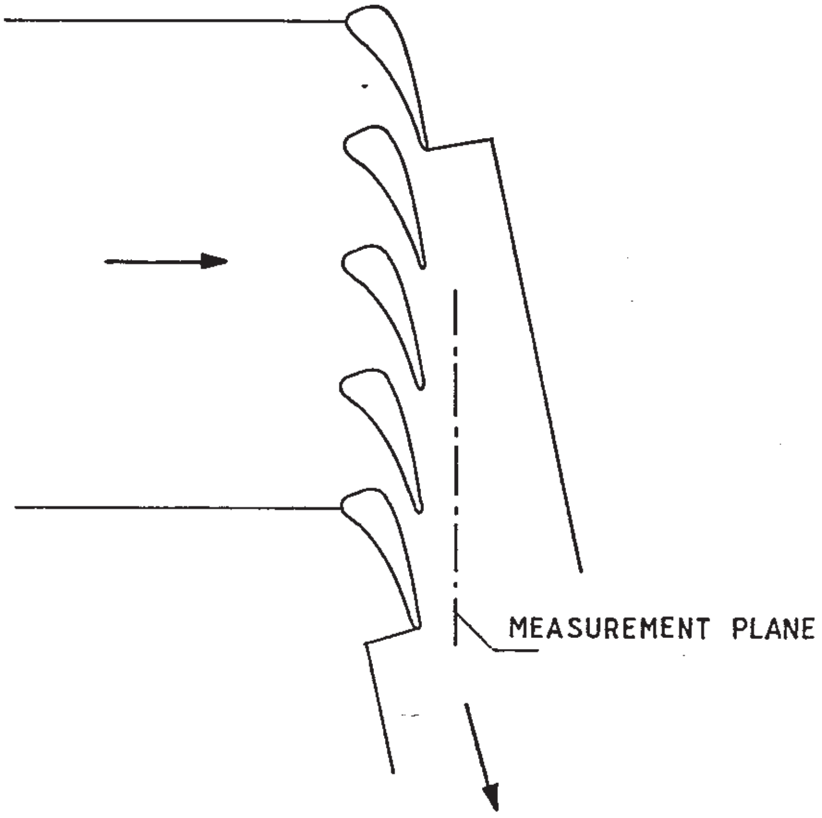
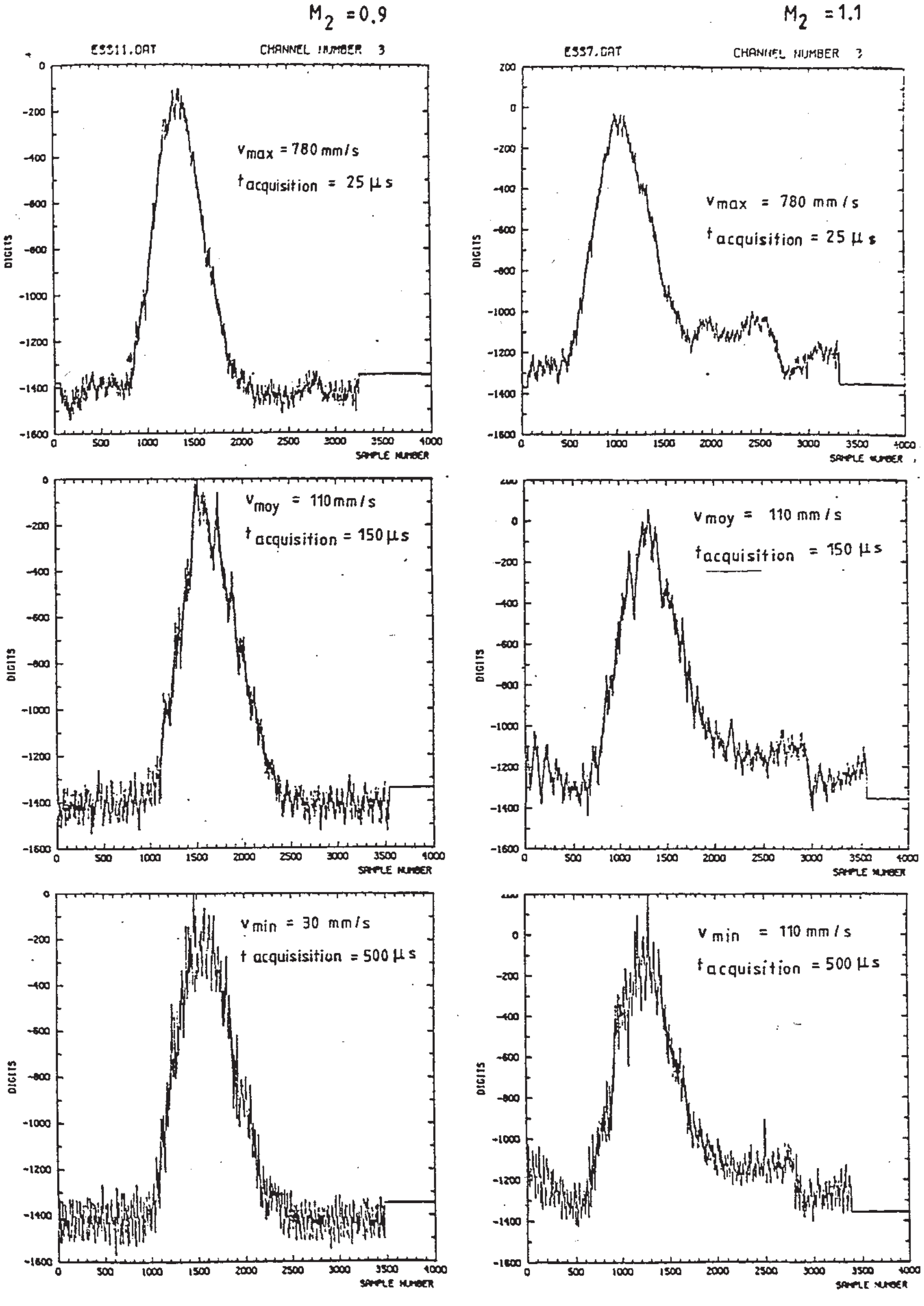


FIG. 8 - TEST SECTION



(a)

(b)

FIG. 9 - RAW TOTAL PRESSURE TRACES FOR VARIOUS PROBE SPEEDS IN COLD FLOW BLOW DOWN TUNNEL

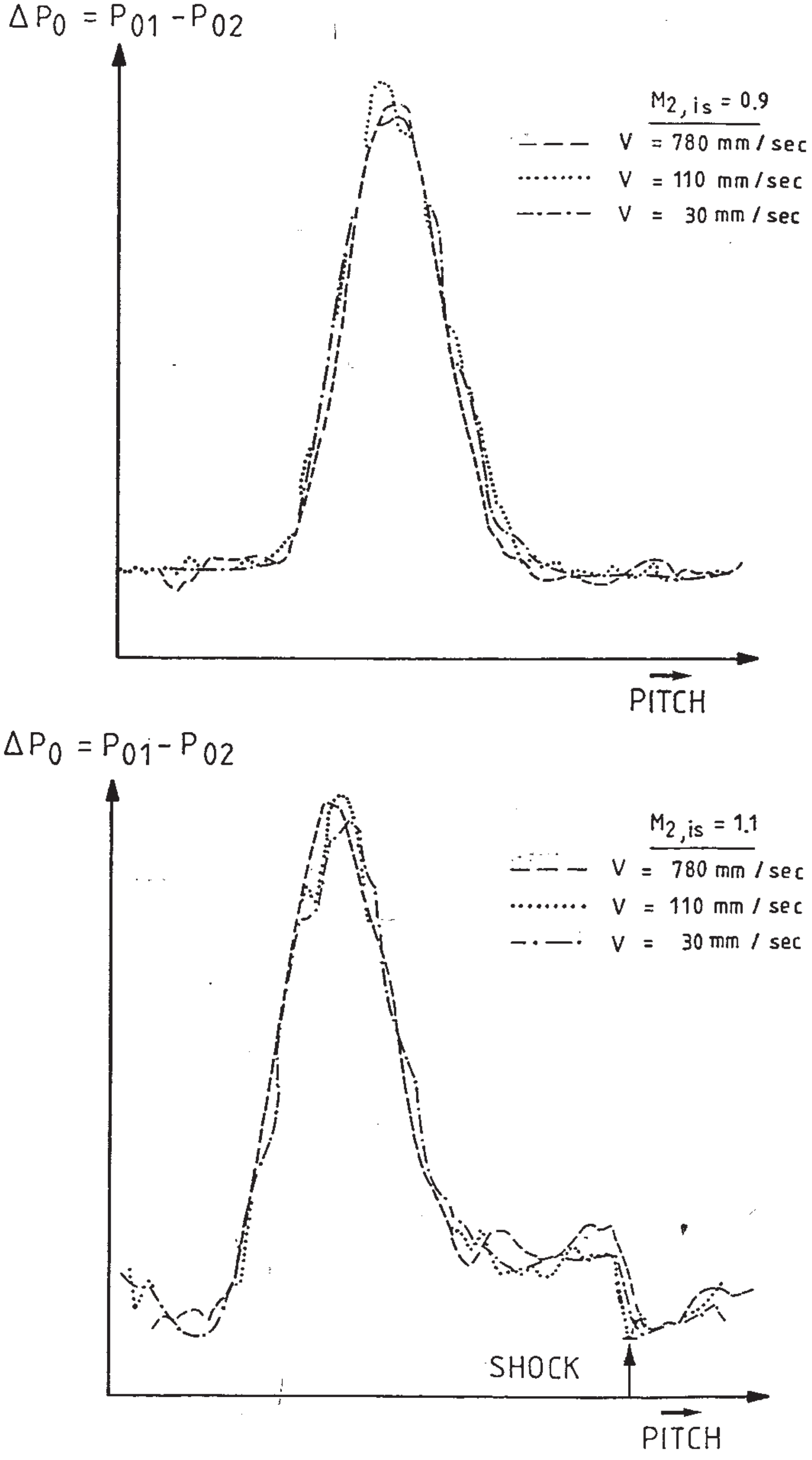


FIG. 10 - VARIATION OF ΔP_0 OVER 1 PITCH FOR VARIOUS PROBE SPEEDS IN COLD FLOW BLOW DOWN TUNNEL. Smoothed data.

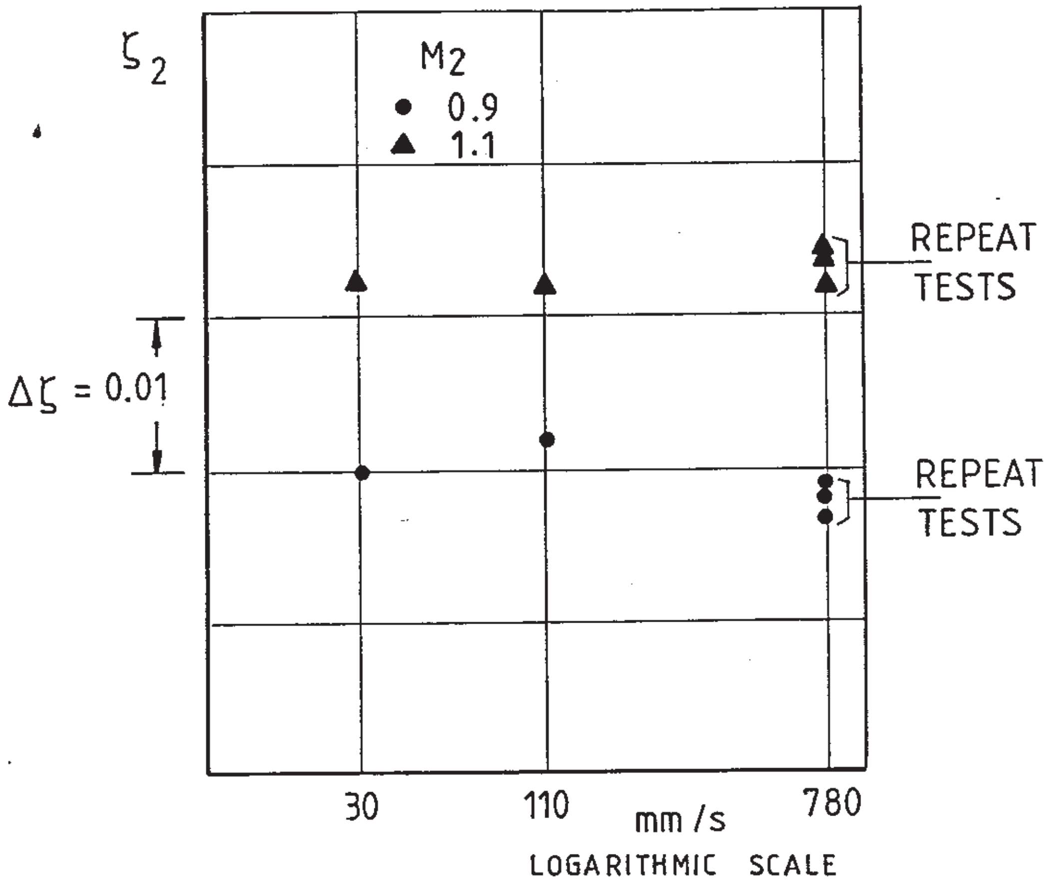


Fig. 11 - EFFECT OF PROBE SPEED ON LOSSES

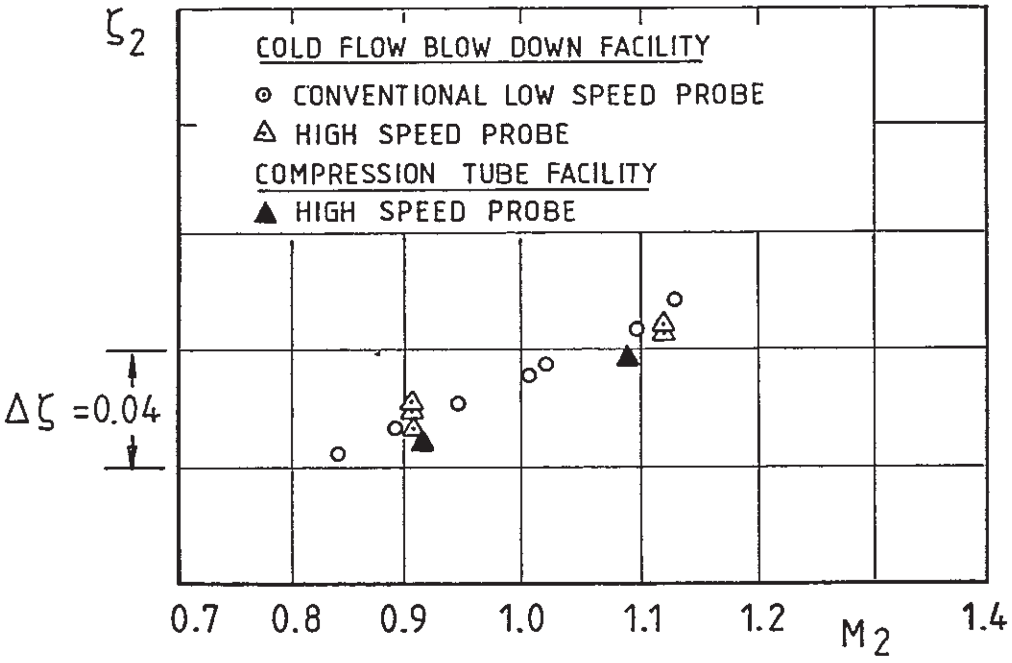


Fig. 12 - COMPARISON OF LOSSES MEASURED WITH LOWSPEED AND HIGH SPEED PROBE TRAVERSING SYSTEMS

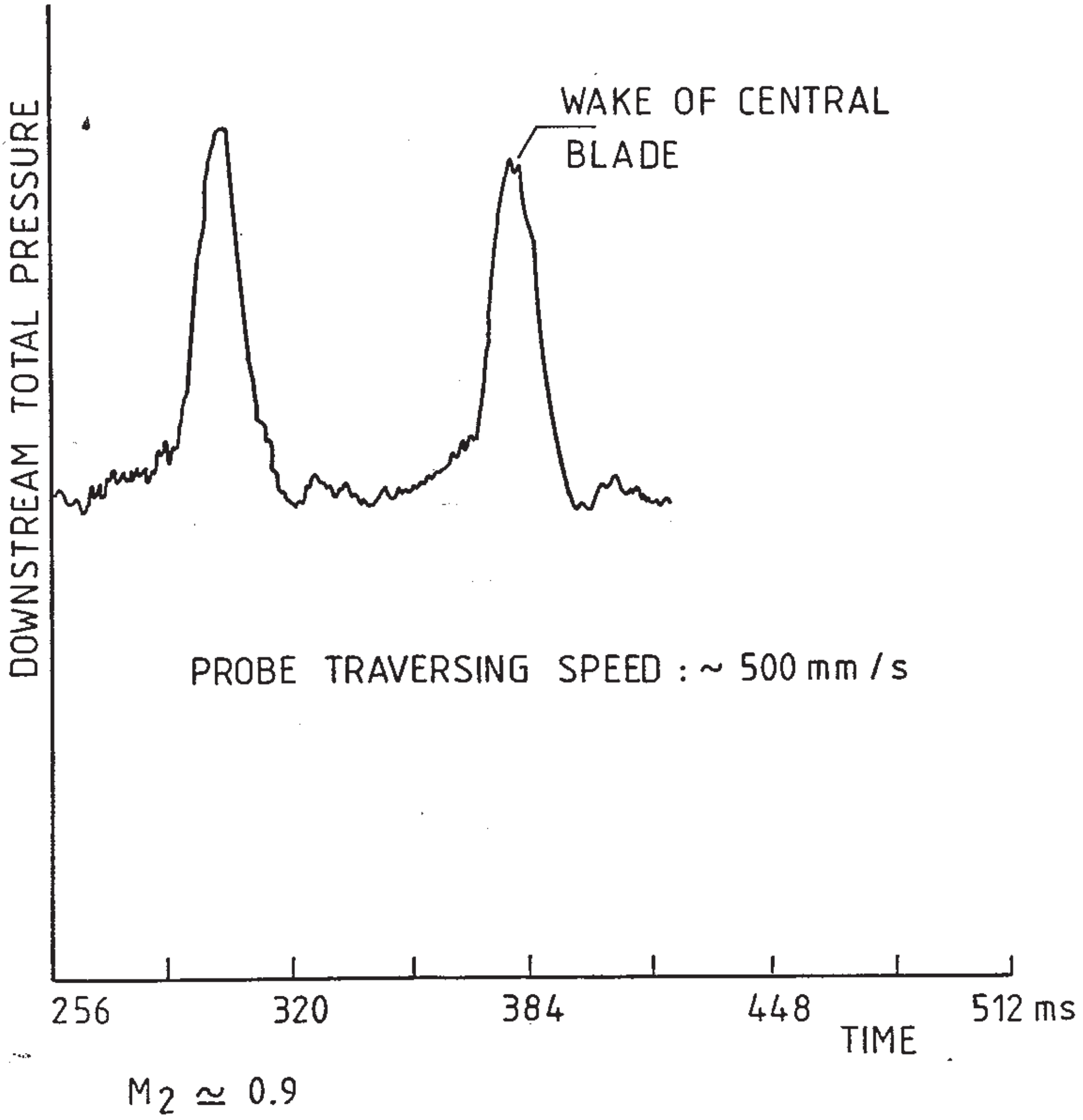


Fig. 13 - VARIATION OF DOWNSTREAM TOTAL PRESSURE OVER TWO PITCHES IN COMPRESSION TUBE CASCADE TUNNEL