# The Dynamic Response of Capillary Tubes for Use in Miniature Pressure Probes

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## 1. Introduction

Experiences in using pressure probes for flow investigations show that pressure probes are well suited for measurements in stationary flow. Relatively few attention is paid to the question of using pressure probes for unsteady measurements. The problems of flow investigations in unsteady flows are obvious since the unsteady interaction between the probe and the flow has to be investigated. Even when the test section is small compared with the pressure probes size the influence of the probe on the flow may lead to distorted results. On the other hand pressure probes are less costly and more robust in practice than competing measuring techniques like LDA and L2F or hot wire and hot film anemometry.

Since the size of a probe is restricted by the size of available pressure transducers if the transducers are installed in the probes head, some concepts were developed in order to transmit the pressure signals from the probes head to the sensors using pneumatic lines. Furthermore these concepts allow for measurements in aggressive media as well as at temperatures exceeding the transducers operating limits when protecting the sensors against these environmental influences.

As the presented work is concerned with the development of miniature pressure probes for unsteady measurements especially in the hot section of gas turbines the concepts of pneumatic transmission lines are taken up.

In a first overview some more general ideas about the so called long line techniques are presented. The basic concept and the data analysis procedure will be explained. In the following more detailed description the main geometric and physical influences on the dynamic response characteristics of pneumatic transmission lines are discussed. Experimental data is compared with theoretical results obtained by a numerical solution of linearized equations of conservation. Finally experiences using long line techniques are discussed and summarized especially against the background of an appropriate probe design.

## 2. Investigations of unsteady flow with pneumatic pressure probes

The concept of transmitting fluctuating pressure signals using capillary tubes as pneumatic transmission lines requires a knowledge of the dynamic response characteristics in order to correct the measured output signals. For small fluctuations and constant physical parameters the dynamic response characteristic can be given by a transfer function representing the behaviour of the system. As known from system theory the analysis of signals in the frequency domain provides a fast computation of the corrected input signal (fig. 1)

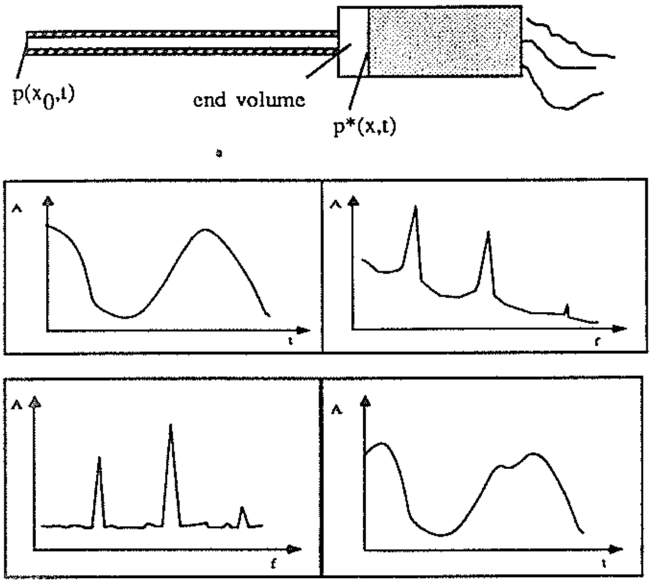

fig. 1: correction of the measured output signal

Since the transfer function depends on environmental parameters as temperature and pressure, the effects of these parameters have to be investigated. Furthermore there is a strong influence of geometry on the pneumatic transmission which has to be taken into account for an appropriate design of probes.

## 2.1 Theoretical investigations

Some basic works are presented by IBERALL (1950) /1/, BERGH and TIJDEMAN (1965) /2/, TIJDEMAN (1975) /3/. IBERALLs contribution gives a relatively complete theoretical treatment of the subject of pressure transmisssion in tubes. On the basis of the fundamental flow equations he derives a solution considering the effects of compressibility and heat transfer as well as short end effects. Proceeding along the same line as Iberall BERGH and TIJDEMAN give a recursion formula for computing the dynamic response characteristic. The computed results are compared with experimental data. Up to frequencies of 300 Hz they find a good agreement between their theoretical investigations and the experimental data. Investigations on the dynamic behaviour at higher freqencies typically for turbomachinery are omitted. In reference /3/ TIJDEMAN presented a numerical solution of the Kirchhoff equation by introducing four non-dimensional parameters. With these parameters the fundamental equations of flow, i.e. the Navier-Stokes equations, the equation of continuity, the equation of state and the equation of energy can be simpilfied. Using this formulation the propagation of a sinusoidal pressure input can be rewritten in the form of equation (1):

$$p\,(x,t) = \left( A \cdot e^{\frac{\omega}{c_s}\Gamma x} + \quad B\ e^{-\frac{\omega}{c_s}\Gamma x} \right) e^{i\omega t}$$

The complex propagation constant $\Gamma$ gives the wave propagation in a tube for small pressure fluctuations. The real part of the propagation constant gives the amplitude attenuation whereas the imaginary part gives the phase shift.

$$\Gamma = f\,(\,s, \nu, Pr, \kappa\,) = \Gamma' + i\,\Gamma''$$

$\Gamma'$ - amplitude attenuation

$\Gamma''$ - phase shift

shear wave number: $s = R\sqrt{(\rho_s \omega/\mu)}$,

reduced frequency: $\nu = \omega R/a_0$,

Prandtl number: $Pr = \mu c_p/R$,

ratio of specific heats: $\gamma = c_p/c_v$

The computed results given in the following report are solved by an algorithm on the basis of this formulation.

## 2.2 Experimental facility

The experimental investigations were carried out using experimental devices as shown in fig. 2.

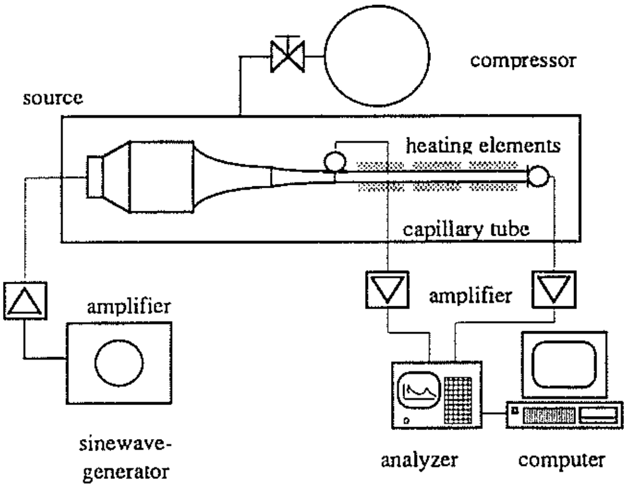

fig.2: experimental devices

The test section consists of three units, e.g. the source generating the signals, the driver section and the signal processing. The electric signals are generated by a sine-wave generator. The amplified and filtered signals in a frequency range from 650 Hz to 20 kHz are converted in mechanical energy by a driver. An exponential horn is used to increase the sound pressure level of the output. With this facility pressure levels of 170 dB can be generated. The test section consists of a pressure cell in which the static pressure can be changed within 1 and 6 bar. For the investigation of the influence of a temperature distribution along the capillary tube electric heaters are used. The heating elements are capable for temperatures reaching 500 °C. The pressure fluctuations at the in- and output are measured using Kulite XCQ-062 miniature pressure tranducers. For the spectral analysis and the determination of the transfer function a FFT-analyzer is used. The post processing and the storage of the data is done on an IBM standard computer.

## 3. Experimental and theoretical results

As the velocity of sound is a function of the temperature a strong dependence of the dynamic response characteristic on the temperature distribution must be expected (fig. 3).

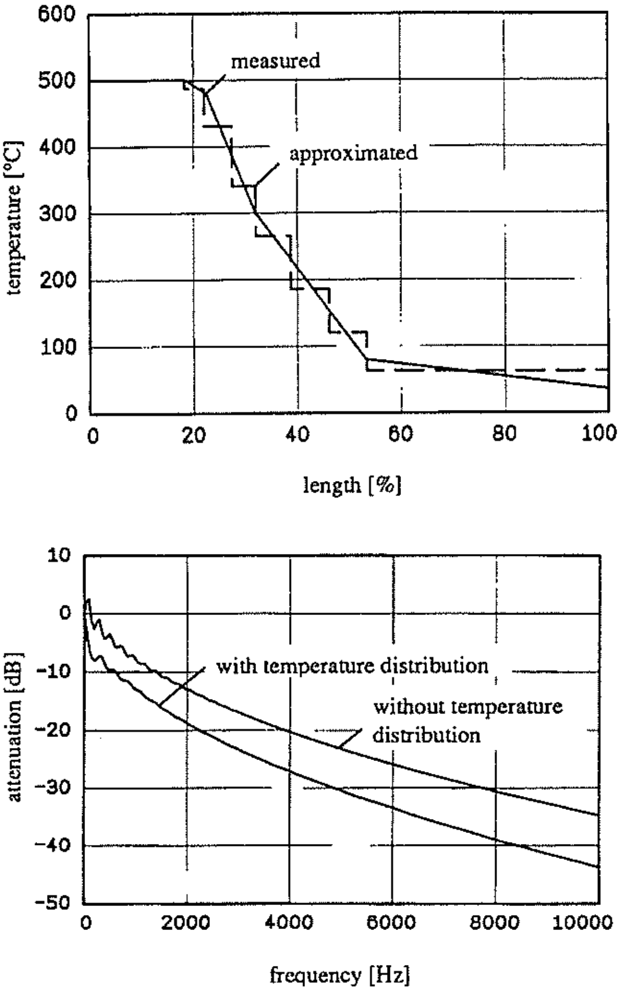

fig. 3: influence of a temperatutre distribution

The result of the transfer function presented in fig. 3 is computed approximating the continous temperature distribution by segments of constant temperatures. In order to show the strong influence of the temperature also the transfer function neglecting the temperature distribution is plotted. As shown in fig. 4 the theoretical obtained results find a good agreement with experimental investigations.

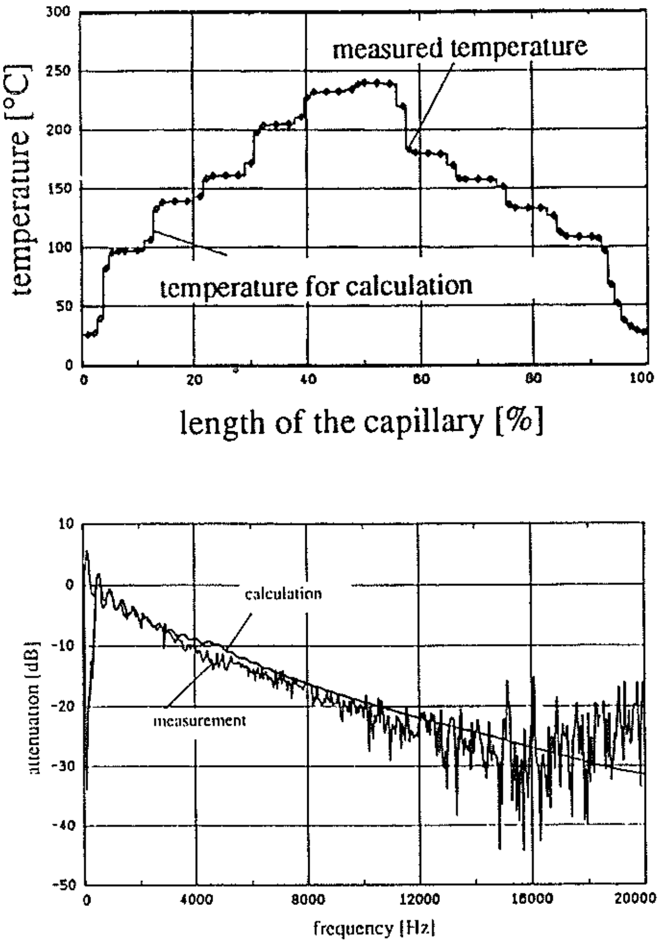

fig. 4: experimental investigation of the influence of a temperature distribution

For a given temperature profile along the capillary the computed and the experimental results are shown. Within frequencies of 10 kHz the agreement is sufficient whereas in the higher frequency range the low signal to noise ratio leads to distortions.

For a capillary tube with a length of 360 mm and a diameter of 0.8 mm the dependence of the attenuation on the static pressure is shown in fig. 5. Three frequencies at a sound pressure level of SPL=145 dB are taken. For lower frequencies an exponential decrease of attenuation with increasing pressure can be determined.

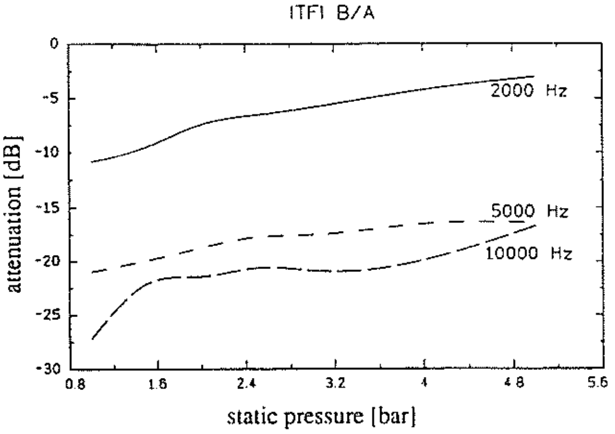

fig. 5: influence of static pressure

Since the theoretical results are obtained by linearized equations of conservation using the assumption of comparable small fluctuating values the dependence of the transfer function on the pressure fluctuations has to be investigated. For high pressure fluctuations non linear effects occur leading to signal distortion. Since the velocity of sound depends on temperature, higher amplitudes propagates faster than lower. This leads to the appearance of shock waves with the form of a sawtooth signal. Since the spectrum of a sawtooth signal differs from a sinusoidal signal in the way that higher harmonic frequencies appear, these frequencies have to be taken into account correcting the measured output signal. Fig. 6 shows the dependence of the attenuation on the sound pressure level of the input signal within the range from 128 dB to 168 dB for a tube with l=400 mm and d=1.0 mm.

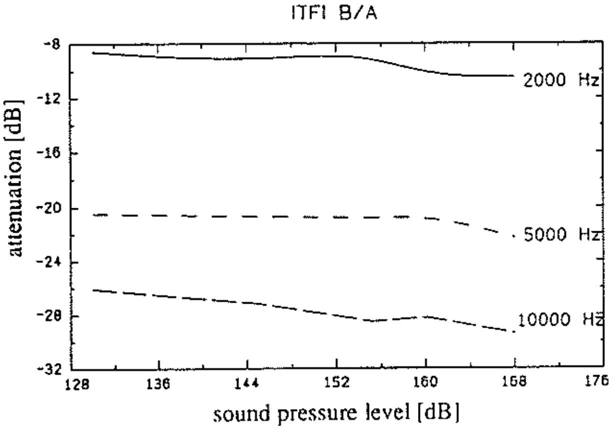

fig. 6: influence of sound pressure level

In the range of the investigated input signals no non linear effects occur and a correction of the transfer function due to non linear effects can be omitted.

Apart from the above mentioned physical parameters the dynamic response of a pneumatic transmission line is determined by its geometry. As the lines become long or small in diameter the quality of the signals decreases due to wall friction and heat transfer. For an appropriate probe design it is therefore necessary to look at the requirements the probe should fulfill. The frequency resolution as well as the coherence between the input and output signals are mainly determined by the probes geometry (fig. 7 and fig. 8).

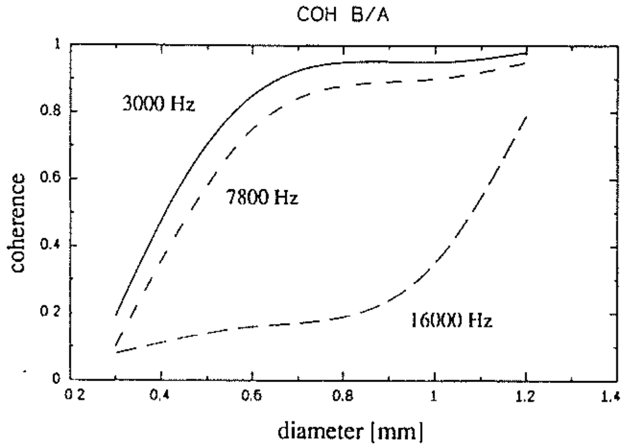

fig. 7: influence of the tubes diameter

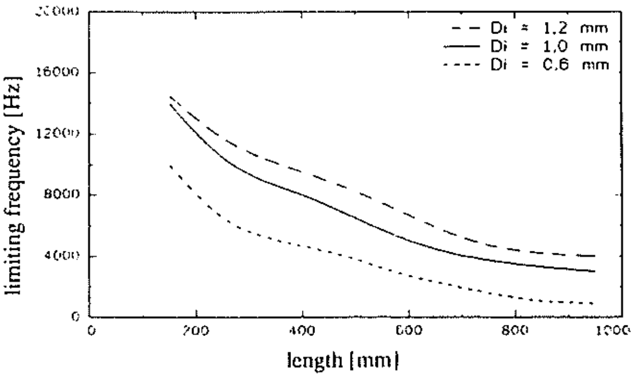

fig. 8: influence of the tubes length

In these figures the coherence function is used as a measure of the quality of transmission. In fig. 7 the coherence functions for three frequencies of capillary tubes of different diameters with a length of l=360 mm are shown. Within frequencies of 10 kHz the diameter should be 0.6 mm in order to reach a value of coherence greater 0.8. The same relation for the influence of the length is presented in fig. 8 introducing a limiting frequency as a function of diameter.

## 3. Conclusions

The problems of measuring techniques for unsteady flow is discussed. Even at high temperatures the robust probe measuring technique is a suitable technique for unsteady flow investigations when installing the sensors at the end of a pneumatic transmisssion in order to get the time dependent input signal the measured output has to be corrected by the dynamic response characteristic of the probe. In this context theoretical and experimental invetigations are carried out in order to get detailed informations about the different parameters influencing the dynamic response. Within a frequency range of 10 kHz a good agreement between experimental and theoretical data is found.

## 6. References

/1/ Iberall, A.: Attenuation of oscillatory pressures in instrument lines. (Research Paper RP2115, Vol. 45, 1950).

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/3/ Tijdeman, H.: On the propagation of sound in cylindrical tubes. (Journal of Sound and Vibration (1975) 39 (1), 1 - 33).