ON THE IMPACT OF TUBE DIMENSIONS OF PNEUMATIC PROBES ON THE RESPONSE TIME

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ABSTRACT

This paper presents an experimental study on the influence of the design of measuring tubes on the response time of pneumatic probes. A parametric investigation on the effect of different combinations of lengths and diameters of sections of the tube system between probe head and pressure sensor was conducted. While the current investigated geometries are similar to that of the original probe, a special focus has been placed on exploring the impact of the dimensions of the first section within the probe head, as well as the length of the flexible tube to the pressure transducer. A comparison performed between the experimental results and a correlation according to Wuest [1] demonstrates good qualitative agreement; however, a considerable offset is observed in the absolute values.

NOMENCLATURE

A	tube cross section
C	electrical capacity
d	tube diameter
f_s	sampling frequency
L	electrical inductance
l	tube length
p	pressure at response time t_p
p_0	initial pressure
p_1	target pressure
q	electrical charge
R	electrical resistance
t_p	response time
V	tube volume
μ	kinematic viscosity of air
ρ	gas density
ϕ	electrical flux

INTRODUCTION

The Institute of Thermal Turbomachinery and Machine Laboratory (ITSM) at the University of Stuttgart features a number of different facilities, such as steam turbine [2], [3] and diffusor test rigs [4], in which flow fields are investigated using pneumatic multiple-hole probes. These probes are mounted on traversing systems to acquire data along the radial direction at different locations. Due to the change in flow velocities and angles in the test rigs, the position of the probes has to be adjusted in the flow field leading to a pressure change at the probe head. The *response time* marks the time required for the change in pressure at the probe head to be visible by the pressure transducer. It is mainly dependent on the geometry of the measuring tubes between the probe head and the transducer, and generally increases with increasing length and decreasing tube diameter. This in turn directly affects the time necessary for conducting measurements and hence the duration and costs of experiments. Therefore, a balance between the requirement for small scale probes, in order to increase accuracy and reduce the influence on the flow field to be measured, and the desire for short tubes with relatively large diameters has to be established.

The goal of this study was to gain the ability to predict the response time of future measurement systems more accurately and to develop design guidelines for optimized probe geometries with respect to their response time. To achieve this, different dimensions of tube geometries were experimentally studied with reference to the difference in their response times, and compared to analytical models in the literature.

ANALYTICAL MODELS

According to Wuest [1], the response time of a measuring tube system is defined as the time taken for a pressure step of $\Delta p = (p_1 - p_0)$, at the measuring position, to be recorded by the pressure transducer (see Fig. 1). For analyzing purposes, the targeting pressure has been changed from 99% to 95% of the final pressure in this paper.

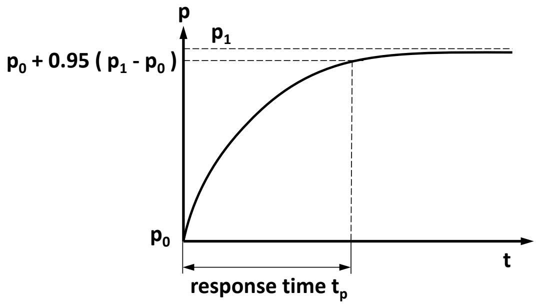

Figure 1: Definition of response time t_p

Then, the response time t_p for a single tube with a pressure transducer can be calculated as:

$$t_p = \frac{128\mu V l}{\pi d^4 p_1}\left[\ln\frac{p_1 + p_t}{p_1 - p_t} - \ln\frac{p_1 + p_0}{p_1 - p_0}\right]. \qquad (1)$$

In contrast to this simple relation between response time and tube geometry, the investigated tube geometries in multiple-hole probes are more complex as they consist of multiple sections.

To counter the varying diameters and lengths in such tube systems, Wuest [1] suggests calculating an equivalent length l_e using an equivalent diameter d_e and the dimensions of the tube geometries, as displayed in Equation (2).

$$l_e = l + d_e \sum_{i=1}^{n} \frac{l_i}{{d_i}^4} \qquad (2)$$

Bergh and Tijderman [5 developed a model that predicts the response time of pressure measuring systems with varying tube geometries. The model provides a recursive formula based on the following fundamental flow equations: the Navier-Stokes equation, the equation of continuity, the equation of state and the energy equation.

At the recent ASME Turbomachinery Technical Conference and Exposition 2016, Grimshaw and Taylor [6] presented an analytical model based on the work of Taback [7] which uses the analogy of an electrical circuit to predict response time. Figure 3 shows the comparison of the tube and the analog circuit model for $n = 3$ tube variations.

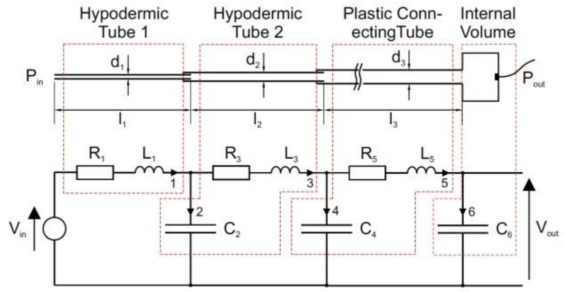

Figure 2: Probe with varying geometries and analogous electric circuit model [6]

This approach results in a system of differential equations of the order $2n$ and represents a much simpler model than that of Bergh and Tijderman [5] (see Equation (3) for three different tubes).

$$\begin{bmatrix} \frac{d\phi_1}{dt} \\ \frac{d\phi_3}{dt} \\ \frac{d\phi_5}{dt} \\ \frac{dq_2}{dt} \\ \frac{dq_4}{dt} \\ \frac{dq_6}{dt} \end{bmatrix} = \begin{bmatrix} -R_1 & 0 & 0 & -1 & 0 & 0 \\ 0 & -R_3 & 0 & 1 & -1 & 0 \\ 0 & 0 & -R_5 & 0 & 1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{\phi_1}{L_1} \\ \frac{\phi_3}{L_3} \\ \frac{\phi_5}{L_5} \\ \frac{q_2}{C_2} \\ \frac{dq_4}{C_4} \\ \frac{dq_6}{C_6} \end{bmatrix} + \begin{bmatrix} V_{in} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (3)$$

The analogous electric circuit parameters R_i, C_i and L_i can be determined as follows:

$$R_i = \frac{32\mu l_i}{{d_i}^2 A_i} \qquad (3)$$

$$C_i = \frac{V_i}{\gamma p_0} \qquad (4)$$

$$L_i = \frac{\rho l_i}{A_i} \qquad (5)$$

The solution of the system of differential equations gives the output voltage V_{out} corresponding to the measured pressure at the transducer and is for the example shown in Fig. 2 defined as:

$$V_{out} = \frac{q_6}{C_6} \qquad (6)$$

In order to fulfill the goal of developing guidelines for the design of pneumatic measuring probes with multiple sections, the models of Wuest [1] and Grimshaw and Taylor [6] were used to predict the response time of the tube systems and for comparison with the experimental data. In contrast to the complex model of Bergh and Tijderman [5], these models were relatively easy to implement.

EXPERIMENTAL SETUP

As mentioned before, the tube system of pneumatic probes usually consists of three sections (see Figure 2):

(1) Tube with a small diameter for the first section
(2) Intermediate tube with a larger diameter for the second section
(3) Flexible tube leading to the pressure transducer for the third section

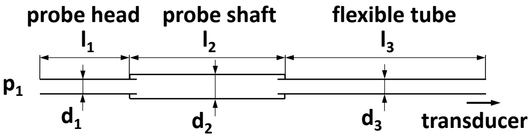

Figure 3: Schematic view of a tube system within a pneumatic probe

In order to investigate the impact of the three sections separately, a parametric study of the tube system was carried out. For a parametric investigation a representative model consisting of four different tube diameters in the first section and three variations in the tube diameters in the second section. This results to 12 combinations of different diameters. Including five different lengths of the flexible tubes, it adds up to a total of 60 combinations that were tested. A summary of all tested parameters is given in Table 1:

Table 1: Overview of investigated parameters

d_1 in mm	d_2 in mm	l_3 in m
0.35	2.0	5
0.5	3.0	7
0.8	4.0	9
1.0		11
		13

The values of the lengths of the first and second sections were kept constant ($l_1 = 0.1$m, $l_2 = 1$m), as well as the diameter of the flexible tube ($d_3 = 1.4$mm). These values were fixed due to the limitations of the probe geometry.

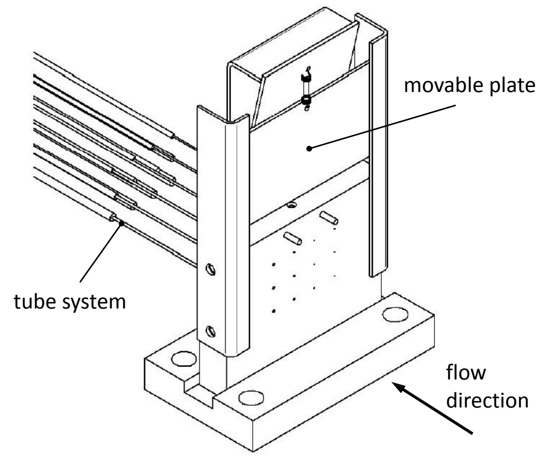

Figure 4: Schematic view of test setup

The pressure tube systems were mounted in front of the low velocity flow test rig while a movable plate covered the tube system from the flow. Via a spring mechanism, the tube system was exposed to a step-like pressure increase of about $\Delta p = 6000$Pa, so that the response time of 12 tube combinations could be measured at the same time. The flexible tubes were connected to a transducer that worked at a sampling frequency of $f_s = 20Hz$. The tests were repeated 20 times for each combination. Fig. 3 shows a CAD drawing of the test setup:

RESULTS

FIRST SECTION

The first parameter that was investigated is the diameter of the first tube d1. This tube was placed in the probe head and has a major influence on the size of the probe head and hence on the accuracy of the probe. The length of these tubes is constrained by the design of the probe head and was therefore kept constant in this study.

In total, four different diameters were tested and compared to the analytical models by Wuest [1] and Grimshaw and Taylor [6]. Fig. 5 shows the results of the experiment and the comparison of the investigated diameters with two representative lengths l_3: 5m (Fig.5 top) and 13m (Fig. 5 bottom). Both models produce the same behavior, whereby as response time increases exponentially with decreasing diameter d_1, a strong increase is predicted by both models when d_1 is reduced below $d_1 = 0.5$mm. The model according to Wuest [1] generally predicts a significantly larger response time compared to Grimshaw and Taylor [6]: the difference between the two increases with increasing length of the flexible tubes from a roughly constant offset of $\Delta t = 1s$ for $l_3 = 5$m (top) to about $\Delta t = 4$s for $l_3 = 13$m.

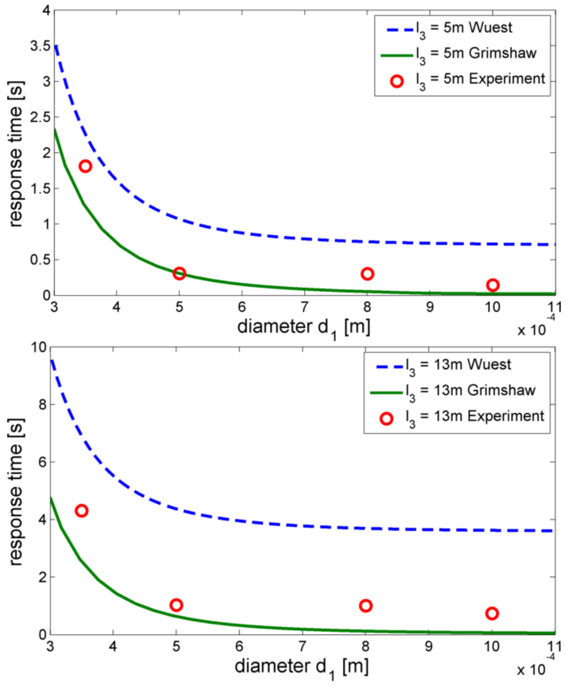

Figure 5: Impact of diameter d_1 on response time with $l_3 = 5\text{m}$ (top) and $l_3 = 13\text{m}$ (bottom) and $d_2 = 2\text{mm}$

The results from this experiment follow the trend of the predicted response times. The sudden increase in the response time from $d_1 = 0.5\text{mm}$ to $d_1 = 0.35\text{mm}$ fits well to the analytical models. Interestingly, the experiment hardly shows any difference in response time for the variation in first tube diameter from d1=0.8mm to 0.5mm.

Table 2 shows the averaged error of the analytical models compared with the experimental results for the different flexible tube lengths. It can be clearly seen that the models by Wuest [1] and Grimshaw and Taylor [6] significantly over and under predict the response time respectively. With about an average 60% error rate across all variations, the analogous electric model according to Grimshaw and Taylor [6] shows a higher accuracy than the model by Wuest [1] (230%) (see Tab. 2).

Table 2: Averaged error over all investigated diameters d_1 compared to analytical models

length l_3	Error Wuest	Error Grimshaw
5m	203.5%	-47.1%
7m	223.1%	-52.6%
9m	228.9%	-57.3%
11m	254.5%	-59.5%
13m	259.5%	-62.8%
average	233.9%	-55.8%

SECOND SECTION

The second parameter investigated was the diameter of the intermediate tube d_2. The tubes in this section connect the tubes coming from the probe head with the flexible tubes leading to the transducer. This tube system is protected by the probe shaft. In this study, the tube length was kept constant ($l_2 = 1\text{m}$) because it was imposed by the design of the actual probes.

Fig. 6 shows the influence of the diameter of the intermediate tube d_2 on the response time for the configuration with $d_1 = 0.35\text{mm}$ and $l_3 = 5\text{m}$. It can be clearly seen that with a larger tube diameter d_2, the response time increases. Again, Wuest [1] over predicts and Grimshaw and Taylor [6] under predict the response time of the system. The trend, on the other hand, fits very well with experimental data; however, the data has roughly the same offset from both analytical models. The behavior was nearly the same for all flexible tube lengths.

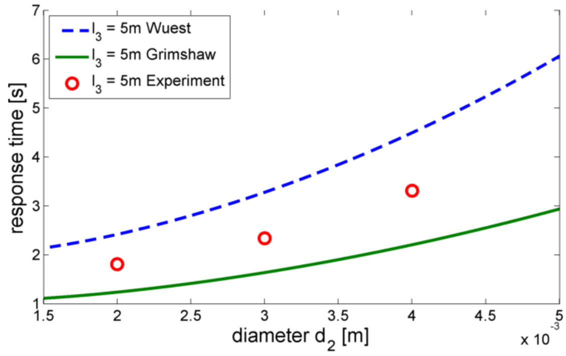

Figure 6: Impact of diameter d_2 on response time with $l_3 = 5\text{m}$

THIRD SECTION

The last section investigated was that of the flexible tube connecting the actual probe with the pressure transducer. Fig. 7 shows that with increasing length of the flexible tube l_3, response time increases linearly. This behavior is qualitatively well predicted by the model of Grimshaw and Taylor [6]. However, the absolute error is high especially for the tube diameter of the first section $d_1 = 0.35\text{mm}$, although this error decreases with larger diameter d_1.

Furthermore, comparing Fig. 7 top and bottom, it can be clearly seen that the slope of the curve increases with smaller diameter d_1. This implies that the choice of the first diameter d_1 has an enormous impact on the increase in the response time per additional flexible tube length.

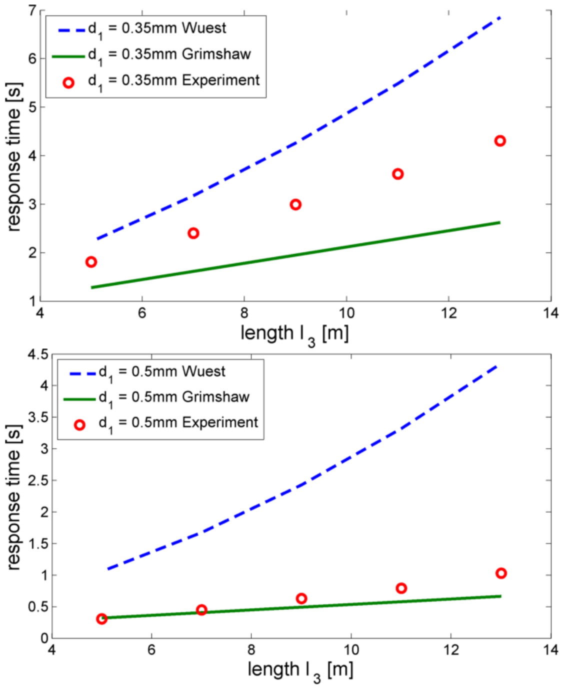

Figure 7: Impact of diameter d_2 on response time with $l_3 = 5\text{m}$ and $d_1 = 0.35\text{mm}$ (top) and $d_1 = 0.5\text{mm}$ (bottom)

POTENTIAL FOR OPTIMIZATION

Since the aim of this study was to provide a tool for a better prediction of the response time, an optimization of the variable parameters was carried out in this section.

To summarize the results from the comparison between the analytical and experimental results it can be stated that for a pneumatic probe with a low response time, it is crucial to select the right diameter for the tubes in the first section, i.e. the probe head. Fig. 5 shows that decreasing the diameter increases the response time exponentially. On the other hand, larger tube diameters result in larger probe heads, which reduce accuracy and resolution (see [6]). As a compromise between these factors, a diameter of $d_1 = 0.35\text{mm}$ was chosen. For a standard pneumatic five hole probe, a set of five tubes arranged in a cross shape is required. Assuming a wall thickness of about $s_W = 0.1\text{mm}$, this leads to a minimal head diameter of $d_H = 1.65\text{mm}$. The length of the tubes in the first section l_1 is determined by the design of the probe head. In general, this length should be kept as short as possible to reduce the high impact of the first small diameter tubes.

For the second section, similar conclusions can be drawn to optimize the response time. Again, the length of this section is limited to the design of the probe which is mostly constrained by the test rig boundary conditions. This leaves only the potential to optimize the tube diameter in this section. Fig. 8 shows that the optimal diameter for the given configuration with a flexible tube length of $l_3 = 5\text{m}$ is at $d_2 = 1.1\text{mm}$. Since the minimal diameter increases slightly with increasing flexible tube length l_3, the optimal diameter lies in the range of $d_2 = 1 \div 1.5\text{mm}$.

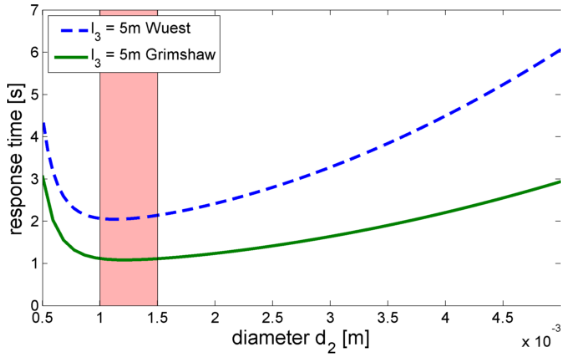

Figure 8: Impact of diameter d_2 on response time with $l_3 = 5\text{m}$

The third section has the most promising potential to optimize towards probes with short response times. It is clear that the distance from the second section to the pressure transducer has a high impact on the response time. In the current test rig applications, this distance was approximately $l_3 = 13 \div 15\text{m}$ long. By placing the pressure transducer next to the traversing system and therefore close to the probe shaft – the second section – the length of the flexible tube has the potential to be reduced to about $l_3 = 1 \div 2\text{m}$. According to the analytical models, this would lead to an improvement of about $\Delta t = 2 \div 5\text{s}$ for a given probe design, see Fig. 9.

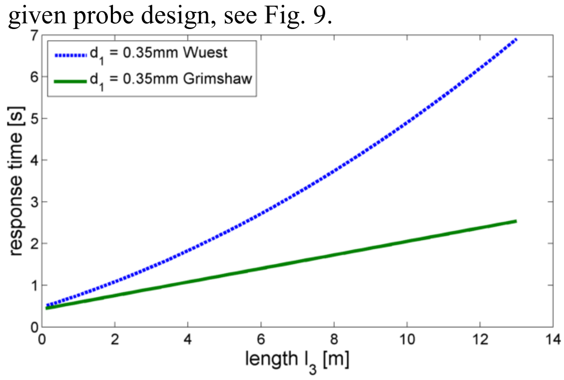

Figure 9: Impact of diameter d_2 on response time with $l_3 = 5\text{m}$

Another parameter that influences the response time of the system is the diameter of the flexible tube d_3. This parameter has not been investigated in the experimental study but, as Fig. 10 shows, it has a large impact on the response time. The investigated configurations make use of flexible tubes with a diameter of $d_3 = 1.4\text{mm}$. Compared with the analytical model [1], the optimal diameter d_3 has already been chosen. On the other hand, looking at the prediction of the Grimshaw model [6], it gives the impression that the optimal diameter lies at $d_3 = 0.7\text{mm}$, with a potential reduction in response time of $\Delta t = 0.5 \div 1\text{ s}$. This highlights the potential for improvements in this section but requires further investigation of this parameter.

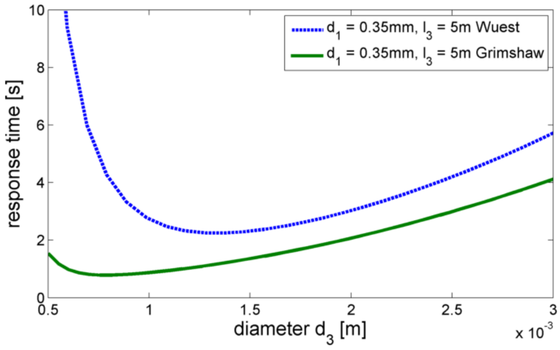

Figure 10: Impact of diameter d_2 on response time with $l_3 = 5\text{m}$

CONCLUSION

In this study, an investigation on the impact of varying tube dimensions on the response time of pneumatic probes, as well as a comparison of experimental data with two analytical models was performed. The results show that neither of the models can accurately predict the response time of the investigated configurations. The model of Grimshaw and Taylor [6] shows better overall agreement than that of Wuest [1], however it still only achieves an agreement of roughly -60% in this study.

Therefore, by taking both models into account, one can get a fairly good prediction of the response time of any combination of tube diameters and lengths. For future developments of pneumatic probes, the following guidelines have been drawn:

(1) For the first section, a balance between achievable accuracy and response time has to be found. A diameter of $d_1 = 0.35\text{mm}$ seems to be a good compromise. Furthermore, the length of these tubes should be kept as short as possible.

(2) The optimal diameter for the tubes in the second section is in the range of $d_2 = 1 \div 1.5\text{mm}$. Again, the length l_2 should be kept as short as possible.

(3) The pressure transducer should be placed as close as possible to the traversing system so that the flexible tubes are kept short. For the given dimensions of pneumatic tubes, the model of Grimshaw and Taylor predicts that every meter saved leads to a reduction of up to $\Delta t = 0.2\text{s}$.

In addition, the study shows the potential of reducing the diameter of the flexible tube d_3 for further improvements to the response time. But since this parameter has not been validated in this study, an optimal value cannot be given at this point of time. The present study hence serves as a platform for further investigations, which could involve the implementation of the model of Bergh and Tijderman [5], in order to improve the agreement between prediction and experimental results.

ACKNOWLEDGMENTS

The authors are especially thankful to the mechanics of ITSM for their support in building the experimental setup.

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