## MODERN AVIATION AND SPACE TECHNOLOGIES

UDC 53.089.6(045)
DOI 10.18372/2306-1472.75.13117

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# RESEARCH ON THE PNEUMATIC LINE LENGTH IMPACT ON THE DYNAMIC PRESSURE MEASURING SYSTEM CHARACTERISTICS

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## Abstract

**Purpose:** to do research on the pneumatic line length impact on the bandwidth of the useful signal and phase shift. **Method:** the processing of experimental data was carried out in MatLab environment, where was constructed the model of transient characteristic, and by using model was determined amplitude-frequency and phase-frequency characteristics. **Results:** the paper considers the experimental results regarding the dynamic calibration of the pressure measurement systems. This system consists of a pressure sensor and a pneumatic line that connects the sensor and the inlet pressure receiver. As a result of research, the amplitude-frequency and phase-frequency characteristics of the measuring system were obtained for different values of the pneumatic line. The paper also specifies the recommendations how to select lengths of the pneumatic line from the pressure receiver to the sensor when measuring pressure pulsations. **Conclusion:** for the Motorola MPXV5004DP sensor, the studies have been carried out in order to determine the impact of the pneumatic line length on the bandwidth and phase shift. During research, specific interrelations have been obtained. By means of these interrelations, it is possible to estimate the limiting transmission frequency and the phase lag of the measuring system. The obtained data allow to provide the correct planning of the experiment and to perform the high quality experiment on the investigation of the dynamic characteristics of the flow interacting with the streamlined object.

**Keywords:** amplitude-frequency characteristics; bandwidth; damping ratio; dynamic gradation; phase shift; phase-frequency characteristics; pneumatic line, pressure sensor, time constant

## 1. Introduction

When carrying out aerodynamic studies related to the distribution of pressure along the aircraft bearing surface, as well as studies of velocity fields characteristics in the nuclei of vortices inherent in various structures, it is necessary to analyze the dynamic characteristics of the flow. As a rule, the measuring system intended for studies of these processes contains a pressure receiver, a pneumatic line, and a pressure sensor respectively. The most critical element of this stucture is the length of the pneumatic line on which the dynamic characteristics of the measuring system depend. Therefore, this paper is dedicated to the research concerning the pneumatic line length impact on the dynamic pressure measuring system characteristics.

## 2. Analysis of recent research and publications

A connecting tube between the measured object and the pressure sensing element is a common component part of pressure measurement systems. Dynamic characteristics of the resulting fluid oscillator may significantly influence the

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magnitudes of dynamic measurement errors [1-3]. This paper presents an experimental analysis of dynamic characteristics of connecting tubes of different lengths and diameters. Inlet step pressure changes were generated by a system of two loudspeakers [4-5], but this method allows to calibrate in a small range of pressure changes

## 3. Description of the experimental installation

To conduct research, an experimental installation was created. The installation consists of the following components:

- Freescale Semiconductor MPXV5004DP integrated pressure sensor: operating pressure range –from 0 to 3,92 kPa (0÷400 мм H2O), power supply – 5B, measurement accuracy – 2,5% of the full scale [6];
- MMH-2400(5)-1 micromanometer: operating pressure range – from 0 to 2,354 kPa (0÷240 мм H2O), measurement accuracy – 1% [7];
- PCI-6025E (12 bit , 200 kHz) multifunctional ADC board intended to convert sensor analog signals into the digital domain. [8];
- Software environment for data acquisition, processing and visualisation – LabVIEW [9];
- Software environment for final data processing – MatLab [10].

All components of the experimental installation are shown in fig. 1.

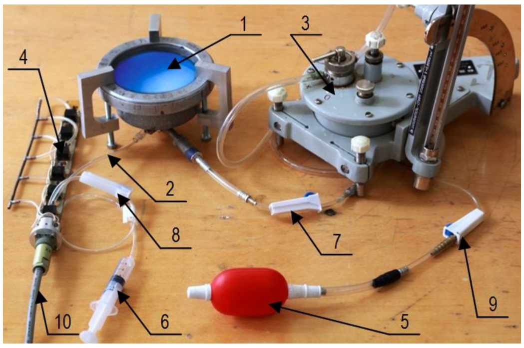

Fig. 1. Experimental installation for the measurement system dynamic characteristics

1. Receiver for a pressure variation jump; 2. pneumatic line of a specific length; 3. reference manometer; 4. pressure sensor MPXV5004DP; 5. pump for creating pressure in the system; 6. device for creating a predetermined pressure bias in the system; 7, 8, 9 – shut-off valves of the system; 10. data interface to the PC ADC board (PCI-6025E).

With the rubber pump (5) being used, the experimental installation allows to create the necessary pressure in the receiver (1), the value of which is referred to the manometer (3). To maintain the preset pressure in the receiver, a shut-off valve (7) is applied. The structure of the receiver includes an elastic latex membrane (see Picture A of Figure 2). When the membrane is impacted by a sharp needle heated to 300 °C, its instantaneous rupture occurs and the pressure in the system falls to zero (see Picture B of fig. 2, where the state of the membrane after its rupture is shown). Thus, a pressure variation jump is caused in the system. The application of compact installation adapters leads to the fast connection between pneumatic lines of different lengths, the receiver (1), and the board of pressure sensor MPXV5004DP (4). It should be noted that pipes made of a transparent polymer material with an internal diameter of 2 mm and an outer diameter of 5 mm are used for the pneumatic line. To create a preset pressure in the sensors of the system, a 10 ml syringe (6) is used. Additional shut-off valves (8, 9) make it possible to fix a constant pressure in the specified sections of the system.

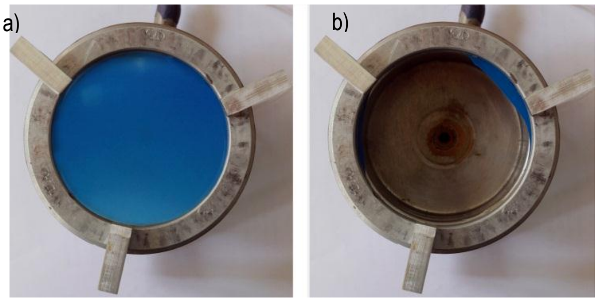

Fig.2 Device for physical modeling of a pressure variation jump in the system: a) the latex membrane under the impact of a preset pressure in the system; b) the membrane after the creation of a pressure jump as a result of its rupture

### 3.1. The experiment order

The pneumatic line length impact on the dynamic characteristics of the measuring system is estimated taking into account its amplitude-frequency and phase-frequency characteristics. A physical experiment is carried out for different lengths of the pneumatic line. As a result of this experiment, a response to the spepwise pressure variation impact has been recorded at the input of the MPXV5004DP sensor. Using the PCI-6025E ADC board, the analog signal of the sensor is sampled with frequencies from 1000 Hz to 30000 Hz. The obtained data are transferred to the LabVIEW software environment where a corresponding data file is generated and a diagram is constructed. The following pneumatic lines have been considered in the experiment: 30mm, 500mm, 1000mm, 2000mm, 3000mm, 4000mm, 5000mm, 5500mm. The experiment for a given length of the pneumatic line has been performed twice to confirm the estimation correctness obtained for the the transient process parameters. Figures 3-6 show the transient process diagrams for different lengths of the pneumatic line.

With an increase in the pneumatic line length, the time of the transient process is also increased. That is why different sampling frequencies of the process are set. The following markings are illustrated on the diagrams given below: an input signal (modelled by the membrane rupture); system response to the input signal (experiment); variation in the transient process, which is calculated by using the obtained model.

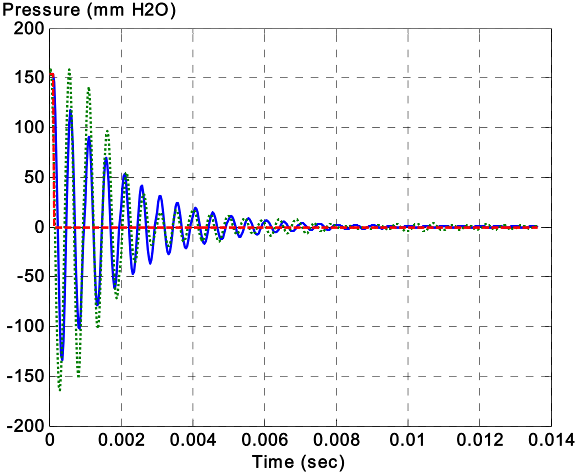

Fig. 3. Recorded pressure jump in the measuring system. Pneumatic line length – 30mm. Sampling frequency – 30 kHz

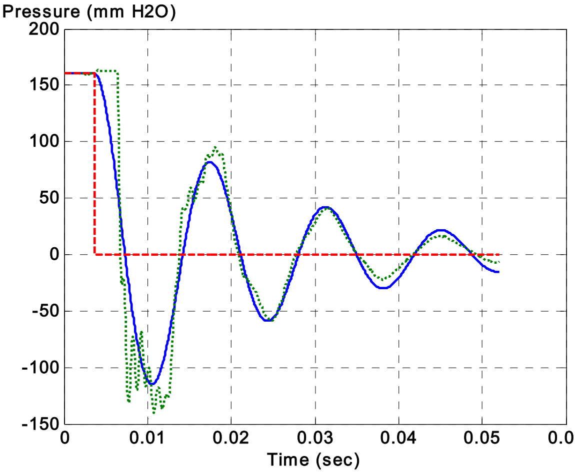

Fig. 4. Recorded pressure jump in the measuring system. Pneumatic line length – 1000mm. Sampling frequency – 20 kHz

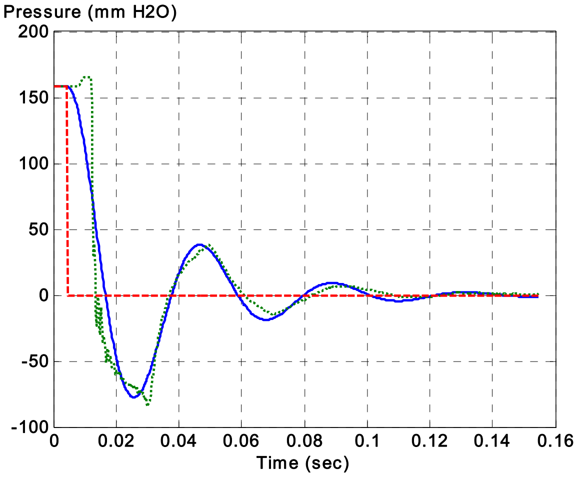

Fig. 5. Recorded pressure jump in the measuring system. Pneumatic line length – 3000mm. Sampling frequency – 5.0 kHz.

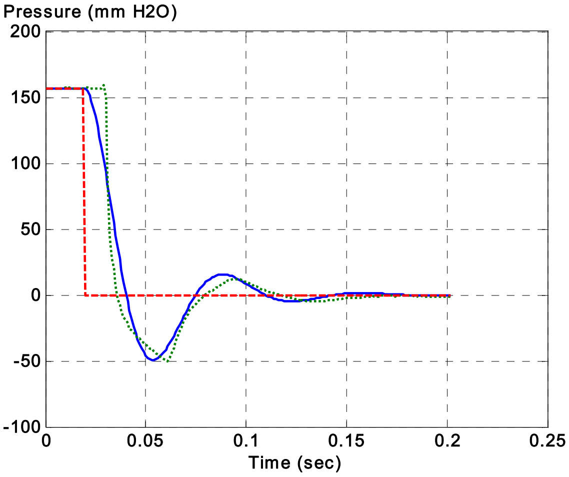

Fig. 6. Recorded pressure jump in the measuring system. Pneumatic line length – 5000mm. Sampling frequency – 1.0 kHz.

As seen from fig. 3,4,5,6, the transient functions obtained as a result of the experiments have an oscillatory transient process, which allows them to be approximated by the following transfer function:

$$W(p)=\frac{k}{T^2p^2+2\xi Tp+}, \qquad (1)$$

where T is the time constant of the system, $\xi$ is the damping factor of the system, $k$ is the amplification factor.

To determine the values of $T$, $\xi$, $k$ search parameters, the MatLab software environment is used. Programs helping to search for unknown parameters T, $\xi$, k are developed, and the amplitude-frequency and phase-frequency characteristics of the measuring system are calculated from the transfer functions (1). The unknown parameters of function (1) are determined applying the simplex search method [11]. This is a direct search method which does not include numerical or analytical gradient values during optimization. In the MatLab software environment, this method is implemented by using the "*fminsearch*" built-in function.

For further data processing, the transfer function (1) should be converted into the following form:

$$W(p) = \frac{a}{p^2 + bp + c}, \qquad (2)$$

where: $b = \frac{2\xi}{T}$; $c = \frac{1}{T^2}$; $a = kc$.

The transfer function (2) given above allows to apply the "Bode" built-in function in order to calculate the logarithmic frequency characteristics (Bode diagrams) [12]. The application of this function makes it possible to determine the following system parameters: bandwidth; resonant frequencies; amplitude and phase stability margin. The bandwidth of the measuring system is the point of interest in the experiment described in this paper. The obtained values of the time constant, damping factor and the bandwidth of the system with a certain pneumatic line length are the required data.

As an example, fig. 7 shows the amplitude-frequency characteristics of the system for different lengths of the pneumatic line on the logarithmic scale. As seen from the presented figure, an increase in the length of the pneumatic line leads to a decrease in the magnitude of the amplitude characteristic resonance peak, as well as a decrease in the frequency at which this peak is located.

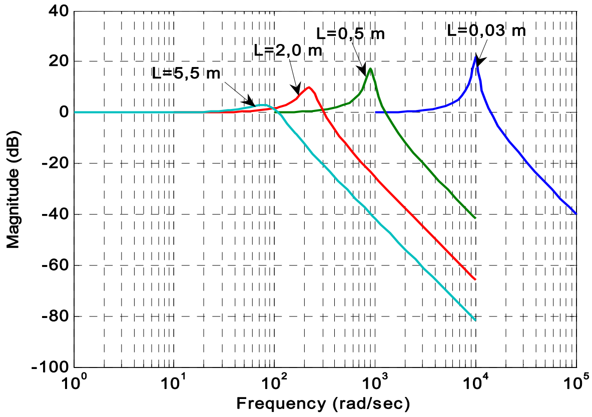

Fig. 7. Amplitude-frequency characteristics of the measuring system depending on the pneumatic line length

Fig. 8 shows the phase characteristics of the system for different lengths of the pneumatic line. These characteristics are necessary to determine the phase shift of the signal at the boundary of the transmission frequency of the system.

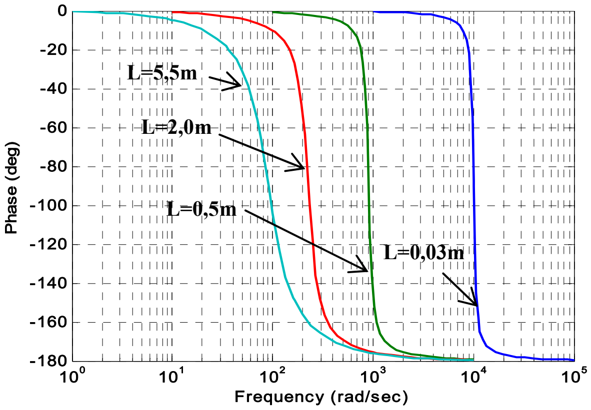

Fig. 8. Phase-frequency characteristics of the measuring system depending on the length of the pneumatic line

### 3.2. Main research results

The experiment makes it possible to determine the parameters of model 1 for pneumatic lines with different lengths. The values of these parameters are presented in tab. 1. In addition, the adequacy of the transient process model obtained as a result of identification has been checked. The mismatch between the model output data and the experimental data has been calculated. A test has been performed to ensure that the resulting sample complies with the normal distribution. To achieve this goal, the built-in Matlab-jbtest function is applied. This test is asymptotic and adequately operable for large samples.

*Table 1*

**The pneumatic line length impact on the characteristics of the measuring system**

| Pneumatic line length, $L$ (mm) | Time constant, $T(s)$ | Damping factor $\xi$ | Transmission frequency, (rad/s) | Phase shift, (deg) |
|---|---|---|---|---|
| 30 | 0.0001 | 0.0416 | 15860 | -178.6 |
| 500 | 0.0011 | 0.0690 | 1432 | -177.2 |
| 1000 | 0.0022 | 0.1057 | 694 | -174.2 |
| 2000 | 0.0044 | 0.1663 | 347 | -167.9 |
| 3000 | 0.0064 | 0.2180 | 210 | -159.9 |
| 4000 | 0.0085 | 0.2807 | 174 | -151.2 |
| 5000 | 0.0103 | 0.3477 | 140 | -139.5 |
| 5500 | 0.0112 | 0.3740 | 129 | -133.2 |

The data $T$ and ξ obtained for model 1 (see Table 1) are approximated by the dependencies in the form of polynomials of the second degree:

$$T(L) = a_0 + a_1 L + a_2 L^2;$$

$$\xi(L) = b_0 + b_1 L + b_2 L^2. \qquad (3)$$

These analytical dependencies allow to calculate the coefficients of model 1 for any given length of the pneumatic line within the limits up to 5.5 m. The values of the obtained function coefficients (3) are given in tab. 2.

*Table 2*

**Functions coefficient values (3)**

| $a_0$ | $a_1$ | $a_2$ | $b_0$ | $b_1$ | $b_2$ |
|---|---|---|---|---|---|
| -0,00011517 | 2,4799e-006 | -8,1618e-011 | 0,039443 | 6,4461e-005 | -5,8763e-010 |

The diagrams calculated with the help of the obtained functions (3) are presented in fig. 9, 10.

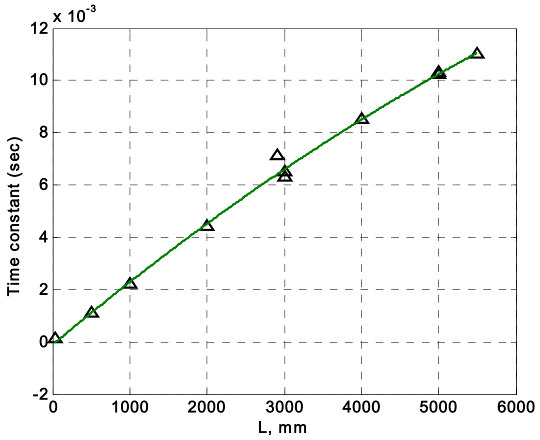

Fig. 9. Impact of the pneumatic line length on the time constant.

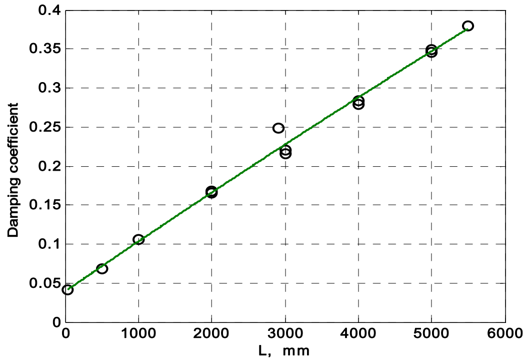

Fig. 10. Impact of the pneumatic line length on the damping factor.

The transfer of the model 1 to the model 2 makes it possible to obtain logarithmic amplitude-phase frequency characteristics of the measuring system for the given lengths of the pneumatic line using the built-in Bode function (see fig. 7, 8). These models are the starting points for calculating the system bandwidth.

The bandwidth of the measurement system is the frequency range from $w_0 = 0$ to the frequency $w_{cf}$, where the following condition is fulfilled:

$$\frac{A_{output}}{A_{input}} = 0{,}707$$

Where $A_{input}$ is the input signal amplitude, $A_{output}$ is the output signal amplitude The frequency at which the signal ratio is equal to 0.707 is the limiting transmission frequency $\omega_{cp}$ of the system. On the logarithmic scale, this ratio is as follows:

$$mag\,\text{dB} = 20\lg\left(\frac{A_{output}}{A_{input}}\right) = 20\lg(0{,}707) = -3{,}01\,\text{dB}$$

Using the obtained diagrams of the amplitude-frequency characteristics of the system, the limiting transmission frequency can be found . The values of the limiting transmission frequency of the system obtained as a result of the experiment are presented in tab. 1. fig. 11 shows the dependence of the limiting transmission frequency of the system from the length of the pneumatic line.

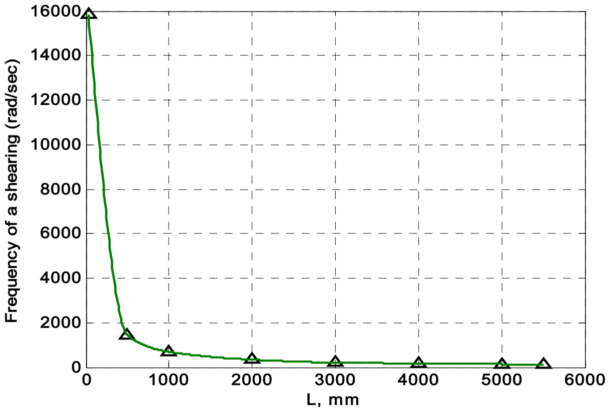

Fig. 11. Length impact on the limiting transmission frequency

As seen from the figure given above, the value of the limiting transmission frequency is significantly reduced with the increase in the pneumatic line length from 30 mm to 500 mm. With a further increase in the length of the pneumatic line (from

500 mm to 5000 mm), the rate of decline in the limiting frequency can be reduced to the greater extent only in case of a significant increase in the length of the pneumatic line. Thus, in order to provide dynamic studies of the flow characteristics, it is necessary to select the pneumatic line length by taking into account the frequency range of the processes included into this research. The dependence presented in fig 11 can be used to adequately select the pneumatic line length depending on the nature of the analyzed processes.

During research, an important role is played by the lag of the measurement system, which is connected with the length of the pneumatic line. This lag can be estimated by the phase-frequency characteristic of the system. The maximum lag value in the system bandwidth is a characteristic for the limiting transmission frequency ωcp (see fig. 8).

Using the functions which are presented in Figure 8, the phase shift between the output and input signals are determined for different values of limiting transmission frequency. The obtained values of the phase shift are presented in Table 1. The diagram which shows the impact of the pneumatic line length on the phase shift value is presented in fig. 12. As seen from fig. 12, an increase in the pneumatic line length leads to a decrease in the phase shift, which is approximately 60 degrees. This situation arises due to the decrease in the frequency of the useful signal transmitted by the system.

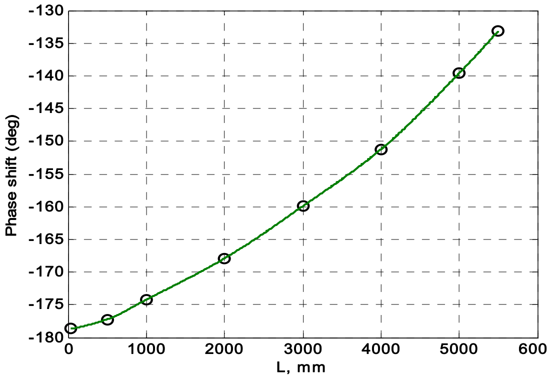

Fig. 12. Impact of the pneumatic line length onto the phase shift

## 4. Conclusion

When performing the studies of dynamic flow characteristics, it is important to take into account the length of the pneumatic line between the pressure receiver and the corresponding sensor. For the Motorola MPXV5004DP sensor, the studies have been carried out in order to determine the impact of the pneumatic line length on the bandwidth and phase shift. During research, specific interrelations have been obtained. By means of these interrelations, it is possible to estimate the limiting transmission frequency and the phase lag of the measuring system depending on the pneumatic line length. The obtained data allow to provide the correct planing of the experiment and to perform the high quality experiment on the investigation of the dynamic characteristics of the flow interacting with the streamlined object.

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### Дослідження впливу довжини пневмотраси на динамічні характеристики системи вимірювання тиску

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**Мета:** провести дослідження впливу довжини пневмотрасси на смугу пропускання корисного сигналу і фазовий зсув. **Метод:** обробка експериментальних даних здійснювалася в середовищі Matlab, де будувалася модель перехідної характеристики, а по моделі амплітудно-частотні та фазо-частотні характеристики. **Результат:** Наведено результати експериментальних досліджень динамічного калібрування вимірювальної системи, що містить датчик тиску і пневмотрасу, яка з'єднує датчик і вхідний отвір приймача тиску. В результаті проведених випробувань отримано: амплітудно-частотні, фазо-частотні характеристики вимірювальної системи при різних значеннях довжини пневмотрасси. Запропоновано рекомендації щодо вибору довжини пневмотрасси від приймача тиску до датчика при вимірюванні пульсацій тиску. **Висновок:** для датчика Motorola MPXV5004DP були проведені дослідження, щоб визначити вплив довжини пневматичної лінії на ширину смуги і фазовий зсув. Під час досліджень отримано конкретні залежності. За допомогою цих залежностей можна оцінити частоту зрізу та фазовий зсув вимірювального каналу. Отримані дані дозволяють коректно зробити планування та провести високоякісний експеримент при дослідженні динамічних характеристик потоку, що взаємодіє з обтіченим об'єктом.

**Ключові слова:** амплітудно-частотні характеристики; датчик тиску; динамічне калібрування; коефіцієнт демпфірування; пневмотраса; постійна часу; смуга пропускання; фазовий зсув; фазо-частотні характеристики

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### Исследование влияния длины пневмотрассы на характеристики измерительной системы динамического давления

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**Мета:** провести исследования влияния длины пневмотрассы на полосу пропускания полезного сигнала и фазовый сдвиг. **Метод:** обработка экспериментальных данных осуществлялась в среде Matlab, где строилась модель переходной характеристики, а по модели амплитудно-частотные та фазо-частотные характеристики. **Результат:** приведены результаты экспериментальных исследований динамической градуировки измерительной системы, содержащей датчик давления и пневмотрасу, соединяющей датчик и входное отверстие приемника давления. В результате проведённых испытаний получены амплитудно-частотные, фазо-частотные характеристики измерительной системы при разных значениях длинны пневмотрассы. Предложены рекомендации по выбору длины пневмотрассы от приемника давления до датчика при измерении пульсаций давления. **Заключение:** для датчика Motorola MPXV5004DP были проведены исследования, чтобы определить влияние длины пневматической линии на ширину полосы и фазовый сдвиг. Во время исследования были получены конкретные взаимосвязи. С помощью этих взаимосвязей можно оценить частоту среза и фазовой сдвиг измерительного каналу. Полученные данные позволяют корректно провести планирование эксперимента и качественно выполнить сам эксперимент по исследованию динамических характеристик потока, взаимодействующего с обтекаемым объектом

**Ключевые слова:** амплитудно-частотные характеристики; датчик давления; динамическая градуировка; коэффициент демпфирования; пневмотраса; полоса пропускания; постоянная времени; фазовый сдвиг; фазо-частотные характеристики

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