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EXPERIMENTAL IDENTIFICATION OF THE TRANSMITTANCE MATRIX FOR ANY ELEMENT OF THE PULSATING GAS MANIFOLD

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In positive-displacement compressor manifolds there are pressure pulsations due to their cyclic operation. The analysis of pressure pulsations in the compressor manifolds is important for various reasons: they directly affect the quantity of energy required for medium compression due to dynamic pressure charging, or inversely, dynamic suppression of suction and discharge processes; they cause mechanical vibrations of compressed gas piping network, they cause aerodynamic and mechanical noise; they affect the dynamics of working valves in valve compressors, they intensify the process of heat convection in heat exchangers in the gas network. The Helmholtz model used so far, which is the basis for users, who deal with pressure pulsation damping, contains many simplifying assumptions. This is because; a straight pipe segment substitutes each element of the piping system. In many cases this model is insufficient. An attempt of the analysis of other shapes was presented in references [1–3] but only simple geometry elements were considered. In other papers [4–8] the influence of the mean flow velocity caused problems. In the presented method, on the basis of pressure pulsation measurement results, firstly a division into the forward and backward going wave is determined, then the elements of the scattering (transmittance) matrix are calculated defining the installation element. This allows introducing the correction for gas mean velocity. The results of the method using correction for the gas mean velocity have been compared with the results without correction and Helmholtz model showing better accuracy.

1. INTRODUCTION

Pressure pulsation in positive-displacement gas compressor manifolds can significantly affect the quantity of the energy required for gas compression. These effects can be either favourable (by dynamic pressure charging) or negative. They also cause mechanical vibrations of the manifold, noise; they affect the operation of working valves and forced convection in compressor heat exchangers.

This is why the analysis of pressure pulsations is important for both the designer of compression manifolds and the users who introduce modifications.

One of the more difficult problems with this analysis is a proper description of the acoustic effect of gas manifolds. The analysis is based on the classical Helmholtz model in which an element of the piping system is substituted by composition of straight segments of the pipeline of known length and diameter. The four-pole matrix created in this way has transmission properties: i.e., a whole network can be modelled by coupling such elements in series by simple multiplication of their matrices [1–3].

Quite a number of elements of a piping system can be described properly in this way; unfortunately, not all. For example, in the case of oil separators, valves or dampers of special design such a generalization is unacceptable because the model is too simplified.

The calculation and simulation methods from CFD group, on the other hand, are not convenient for these applications, although they are very useful for the analysis of the engine exhaust dampers. This is because the compressor piping system is usually more complex and in some cases can be hundreds of metres long. Therefore, modelling it as a whole by CFD method is time-consuming, both for the computer, but also, what is more important, for a programmer who has to feed all the geometry to the computer.

The aim of the present project was to work out a method that would allow the experimental identification of any element of a gas manifold outside the manifold with no mean flow, and use computed results with flow correction in real compressor installation. The matrix identified by this method, describing the element of installation, would have the features of transmission matrix but would not be based on a simplified model of a pipeline segment.

2. THEORETICAL BASIS OF THE METHOD

The classical Helmholtz model is based on the solution of wave equation for a straight piping section, see equation (2.1). The result is a four-pole matrix as shown in equation (2.2) and (2.3). The elements of this matrix $\{a_{ij}\}$ are calculated for a straight pipe segment. The complex impedance Z with elements $\{z_{ij}\}$ defined by equation (2.4) is used alongside the four-pole matrix. It may be easily transformed both ways A–Z and Z–A. This approach is limited to rather uncomplicated cases (a list of notations is given in Appendix A):

$$\left\{ \begin{aligned} -\frac{\partial p}{\partial x} &= \frac{1}{S}\frac{\partial m}{\partial \tau} + \frac{b}{S} m \\ -\frac{\partial m}{\partial x} &= \frac{S}{c^2}\frac{\partial p}{\partial \tau} \end{aligned} \right\}, \tag{2.1}$$

$$\begin{bmatrix} P_1 \\ M_1 \end{bmatrix} = \begin{bmatrix} \operatorname{ch}\gamma L & Z_f \operatorname{sh}\gamma L \\ \dfrac{1}{Z_f}\operatorname{sh}\gamma L & \operatorname{ch}\gamma L \end{bmatrix} \begin{bmatrix} P_2 \\ M_2 \end{bmatrix}, \tag{2.2}$$

$$\begin{bmatrix} P_1 \\ M_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} P_2 \\ M_2 \end{bmatrix}, \tag{2.3}$$

$$\begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \end{bmatrix}. \tag{2.4}$$

One can introduce

$$\left. \begin{aligned} \gamma &= \sqrt{(b + \mathrm{j}\omega)\left(\frac{\mathrm{j}\omega}{c^2}\right)} \\ Z_f &= \frac{1}{S}\sqrt{\frac{(b + \mathrm{j}\omega)}{\mathrm{j}\omega/c^2}} \end{aligned} \right\}. \tag{2.5}$$

To work out experimental methods of thermodynamic identification of gas manifold elements the following assumptions were used

(a) The identified object can be described mathematically in the same general matrix shape as the Helmholtz model presented above. The matrix elements, however, will not be calculated as for a straight pipe, but will be identified experimentally.

(b) During the experiment, only the interaction between one inlet and one outlet is investigated, assuming that interaction between several branches can be covered by the principle of superposition.

(c) During the experiment, only pressure pulsation at any chosen gas manifold points, before and behind the element, are measured (as in reference [4]). Measurement of pulsating mass flow rate cannot at present be performed in an operating manifold for technical reasons.

(d) The object should be identified outside the manifold and then proper correction for gas mean velocity should be introduced.

The element of a manifold chosen for investigation is between cross-sections $i+1$ and $i+2$ in Figure 1. The pipeline segment, which can be treated as a straight pipe of wave impedance Z_i, connects the analyzed element with the source of excitation, and thus the entrance of the manifold with the positive-displacement compressor. The other outlet from the tested element ($i+2$) is connected with closing impedance Z_k by a straight pipeline of wave impedance Z_{i+2}. Both closing Z_k and entrance of manifold Z_0 connected to the compressor can consist of many various branches and devices but this does not affect the results of the presented investigation.

As mentioned before, pressure pulsations measured at any points i–$i+3$ are composed of a progressive wave and a reflected one. The number of these reflections is infinite because acoustic waves are reflected from both the closing and entrance of the gas manifold. In certain conditions these reflections can intensify or attenuate each other. Here the acoustic wave was divided only into progressive — denoted p^+ and reflected — denoted p^- without defining the multiplicity of its components' reflection. In this way, between any two points (e.g. $i+1$, $i+2$) the following dependencies in the complex domain can be written as

$$\begin{bmatrix} P_{i+1}^{+} \\ P_{i+1}^{-} \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} P_{i+2}^{+} \\ P_{i+2}^{-} \end{bmatrix}. \tag{2.6}$$

Matrix T will be called the matrix of pressure transmittance or the scattering matrix. The dependence between matrices T, A, Z may be calculated.

This dependence is valid for any series connection of elements of matrix $[T_k]$ on the condition that these matrices exist (e.g., a gap in the gas manifold does not have

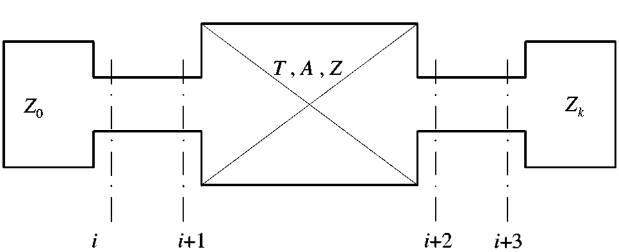

Figure 1. A schematic model of a manifold element for identification purpose, (between the cross-sections $i+1$ and $i+2$, straight pipe i–$i+1$ and $i+2$–$i+3$).

a transmittance matrix because the pressure pulsations on one side are completely independent of the pulsations on the other side). A dividing element can be a valve with strong damping or a large tank, which can be treated as a full opening.

Consider the investigated element for which matrix T existence is assured. Assume, after the model in Figure 1, that the analyzed element is connected with the whole gas manifold by a straight pipeline of wave impedance Z_{fi}, and a pipeline of impedance Z_{fi+2} on the outlet. The general solution of equation of acoustic wave propagation in connecting pipelines is of the same shape as equation (2.2) presented above:

$$\left.\begin{aligned} P_i &= P_i^+ + P_i^- = A_1 \mathrm{e}^{-\gamma x} + A_2 \mathrm{e}^{\gamma x} \\ M_i &= M_i^+ + M_i^- = \frac{A_1}{Z_{fi}} \mathrm{e}^{-\gamma x} - \frac{A_2}{Z_{fi}} \mathrm{e}^{\gamma x} \end{aligned}\right\}. \tag{2.7}$$

The identified four-pole matrix has the same general form as equation (2.3). Equation (2.7) may be also written down for point $i+1$ and for point $i+2$. For the identified element after some substitutions and rearrangements one obtains

$$\left.\begin{aligned} t_{11} &= \frac{1}{2}\left(a_{11} + \frac{a_{12}}{Z_{fi+2}} + a_{21} Z_{fi} + a_{22}\frac{Z_{fi}}{Z_{fi+2}}\right) \\ t_{12} &= \frac{1}{2}\left(a_{11} - \frac{a_{12}}{Z_{fi+2}} + a_{21} Z_{fi} - a_{22}\frac{Z_{fi}}{Z_{fi+2}}\right) \\ t_{21} &= \frac{1}{2}\left(a_{11} + \frac{a_{12}}{Z_{fi+2}} - a_{21} Z_{fi} - a_{22}\frac{Z_{fi}}{Z_{fi+2}}\right) \\ t_{22} &= \frac{1}{2}\left(a_{11} - \frac{a_{12}}{Z_{fi+2}} - a_{21} Z_{fi} + a_{22}\frac{Z_{fi}}{Z_{fi+2}}\right) \end{aligned}\right\}, \tag{2.8}$$

or

$$\left.\begin{aligned} a_{11} &= \frac{1}{2}(t_{11} + t_{12} + t_{21} + t_{22}) \\ a_{12} &= \frac{1}{2} Z_{fi}(t_{11} - t_{12} + t_{21} - t_{22}) \\ a_{21} &= \frac{1}{2}\frac{1}{Z_{fi+2}}(t_{11} + t_{12} - t_{21} - t_{22}) \\ a_{22} &= \frac{1}{2}\frac{Z_{fi+2}}{Z_{fi}}(t_{11} - t_{12} - t_{21} + t_{22}) \end{aligned}\right\}. \tag{2.9}$$

Knowing matrix A, matrix Z for the identified element can be easily calculated.

It follows that knowing the scattering matrix and wave impedance of the connecting pipelines; it is possible to define any matrix of the investigated manifold, which means that the identification of the element is unique.

In this way the following stage of investigation was reached: The basic scattering matrix T was defined; without the necessity of the measurement of the transient mass flow rate; it was found that for the analysis of pulsations in a gas manifold it is practically sufficient to know p^+ and p^-; i.e., pressure waves progressing in opposite directions; how to calculate them will be shown further on in this paper.

One can assume now that it is possible to measure the pressure pulsations in the selected cross-sections of the gas manifold, i.e., i, $i+1$, $i+2$, $i+3$. As a result four functions $p_i(\tau)$, $p_{i+1}(\tau)$, $p_{i+2}(\tau)$, $p_{i+3}(\tau)$ are obtained.

By using Fourier composite transforms, the following dependencies are obtained in the complex domain:

$$P_i(\omega) = F(p_i), \qquad P_{i+1}(\omega) = F(p_{i+1}), \qquad P_i^+(\omega) = F(p_i^+), \qquad P_i^-(\omega) = F(p_i^-), \tag{2.10}$$

$$P_i(\omega) = P_i^+(\omega) + P_i^-(\omega), \qquad P_{i+1}(\omega) = P_{i+1}^+(\omega) + P_{i+1}^-(\omega). \tag{2.11}$$

It can be assumed that element $(i, i+1)$ whose acoustic properties should be defined, is attached to the rest of the gas manifold by two elements $(i-1, i)$ and $(i+1, i+2)$ for which any of A, T or Z matrices are known. Most often these connections are pipelines of diameter D and length L. The acoustic sound speed c in the pipeline is also known. In case of larger lengths the damping coefficient should also be taken into consideration. The impedance matrix Z of such an element has the form of equation (2.4).

Matrix T is calculated from dependence (2.8). By using these last formula equations to define $P_i{}^+$, P_i^-, P_{i+1}^+, P_{i+1}^- can be written as

$$\left.\begin{aligned} P_i &= P_i^+ + P_i^- \\ P_{i+1} &= P_{i+1}^+ + P_{i+1}^- \\ P_i^+ &= t_{11}P_{i+1}^+ + t_{12}P_{i+1}^- \\ P_i^- &= t_{21}P_{i+1}^+ + t_{22}P_{i+1}^- \end{aligned}\right\}. \tag{2.12}$$

The set of equations (2.12) is an algebraic linear set of four equations with four unknowns. It is solved in the amplitude–frequency complex domain. The solution of the set is:

$$\left.\begin{aligned} P_{i+1}^+ &= \frac{P_i - P_{i+1}(t_{12} + t_{22})}{(t_{11} + t_{21}) - (t_{12} + t_{22})} \\ P_{i+1}^- &= \frac{P_i - P_{i+1}(t_{11} + t_{21})}{(t_{11} + t_{22}) - (t_{11} + t_{21})} \\ P_i^+ &= \frac{t_{11}t_{22} - t_{21}t_{12}}{t_{12} + t_{22}} P_{i+1}^+ + \frac{t_{12}}{t_{12} + t_{22}} P_i \\ P_i^- &= \frac{t_{11}t_{22} - t_{12}t_{21}}{t_{21} + t_{11}} P_{i+1}^- + \frac{t_{21}}{t_{21} + t_{11}} P_i \end{aligned}\right\}. \tag{2.13}$$

Dependencies (2.13) allow separating the progressing and returning waves of pressure pulsation in a volumetric compressor manifold. To do this it is necessary to measure the pressure pulsations at two points of the manifold separated by elements of the known matrix T.

For the investigated element, placed between points $(i+1)$ and $(i+2)$, the values of the separated pressure P^+ and P^- at both points are determined in this way.

3. CORRECTION FACTORS FOR MEAN VELOCITY

In compressor manifolds mean flow velocity is usually significant compared to the sound speed and it can affect the velocity of acoustic wave propagation. The mean gas velocity in the manifold may not be known while determining the muffler properties; besides this velocity may change during compressor work, if the load will change. So it is much more convenient to carry out the identification process without flow on the stand outside the manifold. In this case a correction for gas mean velocity should be taken into account in calculations when one wants to use the results in the real installation. This problem has been previously noted [5–8]. The division of the pressure pulsation wave into two separate components travelling forward and backward (reflected one) provides the possibility of introducing the correction factors if the mean velocity is known.

The angle correcting the phase of the pulsation wave may be easily calculated by using the formula

$$\varDelta\varphi = 2\varPi\, w/c. \tag{3.1}$$

By using the formula (3.1) the shift of phase of the travelling forward and backward pressure wave is given by the following formulas:

$$P^{+}_{\varDelta\varphi}(nw) = P^{+}(nw)\,\mathrm{e}^{-\mathrm{i}\varDelta\varphi}, \qquad P^{-}_{\varDelta\varphi}(nw) = P^{-}(nw)\,\mathrm{e}^{\mathrm{i}\varDelta\varphi}. \tag{3.2, 3.3}$$

To determine the wave division in the straight portion of the pipe with small friction the dumping factor b may be neglected and so the pressure wave in equation (2.8) may be simplified to

$$P^{+} = A_1\mathrm{e}^{-\gamma xc/(c+w)}, \qquad P^{-} = A_2\mathrm{e}^{\gamma xc/(c-w)}. \tag{3.4}$$

In the case of a test stand described later in this paper this correction had a significant influence on the result. It has been important because the identification has been done on the stand without the mean flow and the verification on the real compressor manifold with mean flow present. The phase correction is very important when analyzing the pulsation in the refrigerating compressor installation, due to the fact that the sound speed in refrigerants is very low.

4. IDENTIFICATION ON A TEST STAND

On the basis of the theory presented before research was conducted in an attempt to find a method of thermodynamic identification of an element, which could be tested experimentally but before placing the identified element in the manifold.

The idea was to assemble a relatively simple test stand on which it would be possible to minimize the effect of other elements of the installation. The elimination of the effect of gas manifold opening and closing on the calculated matrices was carried out by calculation.

On the test stand (see Figure 2) the mounted element is placed between the pressure pulsation source of regulated frequency and amplitude and outlet pipe closing of known impedance. It is necessary to use at least two closing elements of different impedance Z_{k1} and Z_{k2}, and these two values have to be known. The excitation signal comes from an acoustic loudspeaker.

In the measurement system, before the tested element, pressure is measured at two points P_1, P_2 separated by a pipeline segment of known diameter and length x_{12}. Following the formulae derived earlier, this allows one to determine the pressure progressive and return

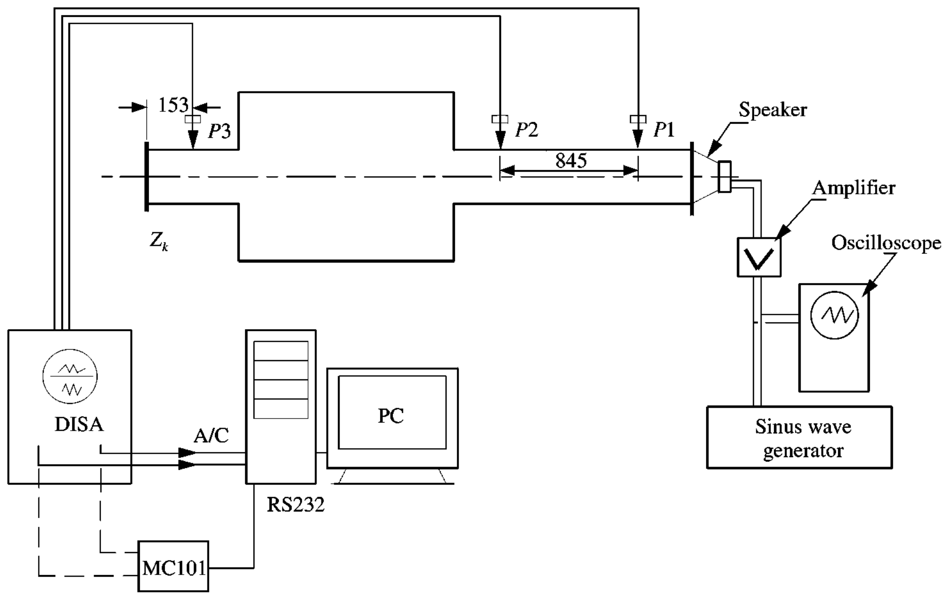

Figure 2. Test stand for the identification of the manifold element.

waves at point P_2:

$$\begin{bmatrix} P_2^+ \\ P_2^- \end{bmatrix}\bigg|_{Z_{k1}} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} P_3^+ \\ P_3^- \end{bmatrix}\bigg|_{Z_{k1}}, \tag{4.1a}$$

$$\begin{bmatrix} P_2^+ \\ P_2^- \end{bmatrix}_{Z_{k2}} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} P_3^+ \\ P_3^- \end{bmatrix}\bigg|_{Z_{k2}}. \tag{4.1b}$$

Upon knowing the closing impedance Z_{k1}, Z_{k2} the progressive and return waves at point 3 can be calculated in the same way. In equations (4.1a) and (b) the scattering matrix T is the same (because the element did not change). After these equations have been written out, a set of equations 4×4 is obtained, which allows one to calculate four unknown elements of matrix T. In this way the identification of the investigated element is unique.

5. APPLICATION OF THE METHOD FOR THE AIR COMPRESSOR MUFFLER

The aim of the experimental verification was to find out whether the identified scattering matrix for the manifold element gives pulsation calculation results more close to reality than the conventional Helmholtz model and what is the influence of the mean velocity correction factor. To this end tests were run on a pressure pulsation damper of special design. The damper had a non-symmetrical structure (see Figure 3). The special shape of the damper was chosen in such a way that in this case the classical Helmholtz model produced significant errors. To determine experimentally matrix T_E outside the manifold a test stand was assembled (see Figure 2).

The pressure pulsation excitation source in front of the damper was an acoustic loudspeaker GDN 16/15 (TONSIL). The loudspeaker was fed from an RC oscillator of

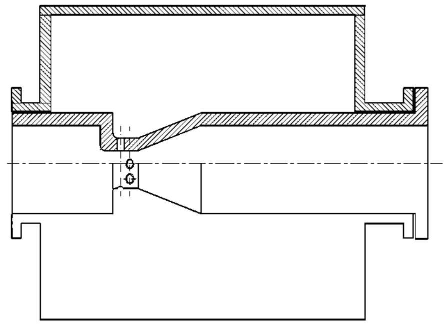

Figure 3. The design of the pulsation damper used for the verification.

20 (Hz)–200 (kHz), by amplifier A20 MK II (PRIMARE). Digital frequency meter PFL-20 measured the frequency and the course of amplified and non-amplified voltage delivered to the loudspeaker was observed on an oscilloscope monitor. The measurement system consisted of three capacitance transducers of pressure Pu2a type produced by DISA. The transducers were connected to an MC-101 Transient Recorder unit by a converter and a DISA amplifying system. The signal was transmitted to the computer by RS-232 and registered for further processing. The variations of pressure pulsations were observed on a DISA oscilloscope. The measurement system was calibrated statically.

The aim of the experiment was to determine the function $p(\tau)$ for three measuring points for various excitation frequencies. It is also possible to use the so-called white noise in the range of measured frequencies, which helps to make the calculations faster. In the experiment described here, however, excitation by single harmonic frequencies was used in order to check the validity of the principle of superposition. The measurement was carried out for two impedances closing the system completely open end, and completely closed end (see Figure 2).

After the measurement and determination of $p(\tau)$ curves, the following calculations were performed: complex functions $P_1(n\omega)$, $P_2(n\omega)$, $P_3(n\omega)$ (where n is the number of harmonic) were determined by Fourier transform; the values P_1, P_2, P_3 determined in the amplitude–frequency complex domain were decomposed for opened and closed systems, from which P_1^+, P_1^-, P_2^+, P_2^-, P_3^+, P_3^- were derived; with data P_2^+, P_2^- and P_3^+, P_3^- for two different closings Γ_k of the investigated system, on the basis of dependencies (4.1a) and (b) elements $\{t_{ij}\}$ of the scattering matrix were determined.

For experimental verification of the calculated matrices a measurement system based on the air compressor S2P216 was used. The compressor operated in a Ward–Leonard system with continuous control of rotational speed possible.

On the stand the tested acoustic damper there was mounted in the compressor suction manifold. The measurement system consisted of DISA capacitance transducers, joined to a transient recorder MC 101 by a converter and an amplifier, and next to the computer. The measured courses of P_2 and P_3 were the basis for the comparison of the results.

6. VERIFICATION OF THE METHOD WITH THE COMPARISON WITH HELMHOLTZ MODEL

On the basis of the pressure pulsation measurements the scattering matrix for the damper shown in Figure 3 has been calculated, for a multiplicity of excitation frequencies 21·7 Hz, which corresponds to a rotational compressor speed of 1300 r.p.m. The average gas velocity

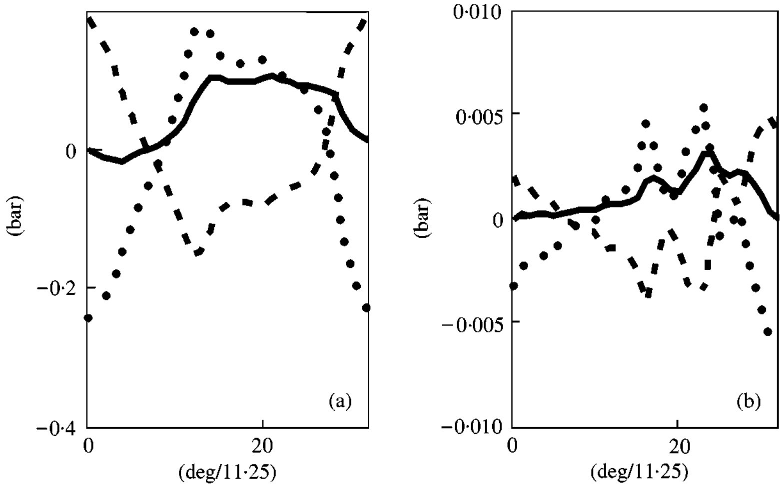

Figure 4. Resolved pressure pulsation at the inlet (a) and outlet (b) of the pulsation damper. Continuous line denotes p, dotted line denotes p^+, and dashed line denotes p^-.

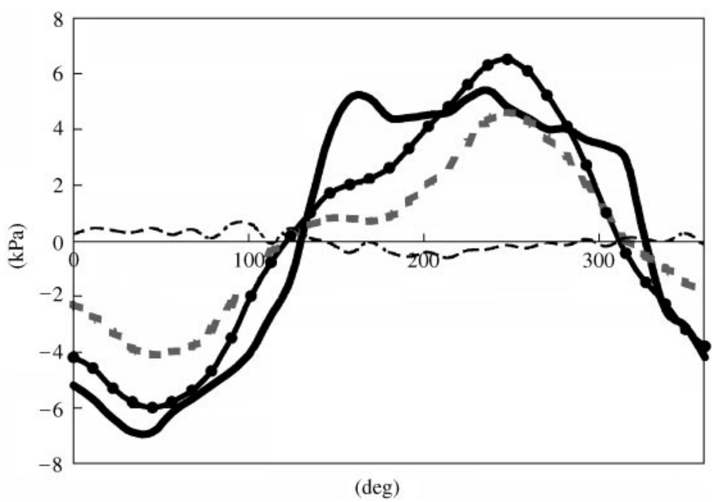

Figure 5. Comparison of the pressure pulsation curves before the damper (P_2) obtained by four methods: ——, measured; —•—, calculated with correction; ▪ ▪, calculated no correction; – · – ·, classic Helmholtz.

was about 5 m/s, which resulted in $\Delta\varphi = 5{\cdot}2°$. This means that the phase difference between forward and backward going waves was $2\Delta\varphi = 10{\cdot}4°$.

After mounting the damper on the test stand at the compressor S2P216 inlet manifold, pressure pulsations were measured for the rotational speed corresponding to these frequencies. The measured pressure pulsations were resolved at similar points 2 and 3 into progressing p^+ and returning p^- components. For 1300 r.p.m. this resolution is shown in Figure 4.

To verify the method real curves of p_3^+ and p_3^- were used. On their basis, by means of the calculated complex transforms: T_E — by the experimental method and T_T — by the classical Helmholtz method, p_2^+, p_2^- and in consequence p_{2T} and p_{2E} were calculated. Then they were compared with the p_2 curves measured on the stand. The comparison of the

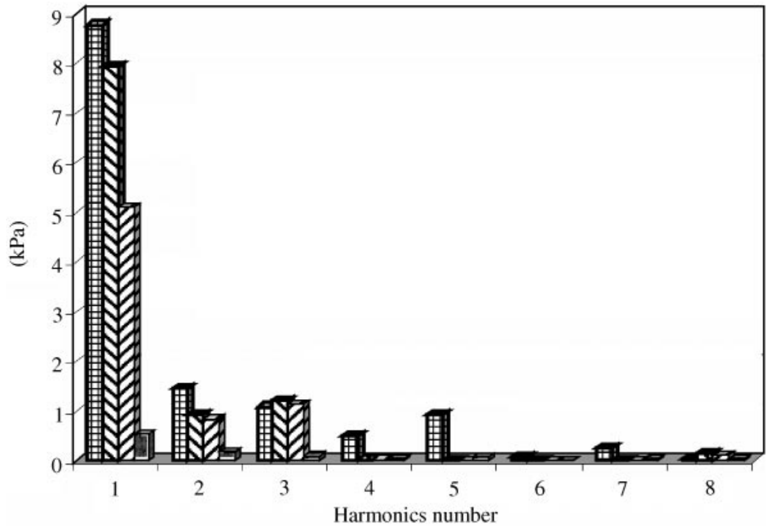

Figure 6. Comparison of the harmonic analysis results for the curves from Figure 5: ▦, measured; ▨, calculated with correction; ▧, calculated no correction; ■, classic Helmholtz.

TABLE 1

Comparison of the peak-to-peak amplitudes of pressure pulsations

(rev/min)	Experiment	Helmholtz method		Identification method without correction		Identification method with correction	
	Δp (kPa)	Δp (kPa)	error (%)	Δp (kPa)	error (%)	Δp (kPa)	error (%)
1300	12·3	1·2	90%	8·7	29%	12·5	1·6%

pressure pulsation curves together with harmonic analysis is shown in Figures 5 and 6. The results were compared with the results obtained without correction for phase difference between forward and backward going waves, as well as with the results obtained in the same way, but with the application of the classical Helmholtz method for determining matrix T.

Table 1 shows the comparison of pressure pulsation peak-to-peak amplitudes.

From the diagrams and the table it follows that definitely better results of identification are obtained by using the experimental identification method presented here. The correction for mean velocity improves the result, but the classical Helmholtz method gives damping of the pulsation damper lower by an order of magnitude, because the pressure amplitudes ratio before and after the damper is smaller.

Similar good results were obtained for the real gas refrigerating compressor oil separator with valves, mounted in the discharge manifold [9].

7. CONCLUSIONS

The most important conclusions of the present paper are as follows.

1. The division of the pressure pulsation wave into two components: forwards and backwards (reflected) going waves provides the possibility of introducing the phase

correction factor for the mean velocity. This correction allows determining the four elements of the scattering matrix independent of the mean local flow existing in the pipe during the tests.

2. This method allows one to introduce a phase correction factor for the mean velocity, in case the identification process is carried out outside the manifold without the mean flow, and then use the results in the manifold with the presence of mean flow. This significantly improves the results in comparison with the calculations without phase correction.

On the basis of the investigation and experimental verification results the following conclusions for these methods can be formulated.

The application of thermodynamic identification methods for complex or non-typical elements of manifold gives only minor errors in comparison with the classical Helmholtz method; introduction of the mean velocity correction further improves the results.

In some cases, when the inner structure of the element is not known, the application of these methods is the only possibility.

The discrepancy in the investigation results and calculations, when certain matrices T are used, results from the following causes: (1) measurement phase and amplitude error when determining matrix T; (2) non-linearity of the phenomenon; since the results processing is linearization in the range of measured parameters, the best results are obtained when the pressure pulsation excitation amplitude during identification tests is of the same order as the one in one real manifold.

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APPENDIX A: NOMENCLATURE

Scalar values

b	flow damping coefficient
c	sound velocity
$m, \dot{m}$	mass flow rate

l	length
p	pressure
S	cross-sectional area
w	velocity
$\dot{V}$	volumetric flow rate
D	diameter

Greek letters

ρ	density
τ	time
ω	frequency

Complex values

$\mathrm{j} = \sqrt{-1}$	imaginary unit
P	complex pressure (after FFT)
M	complex mass flow rate (after FFT)
$\bar{T}$	transmittance

Complex matrices

$A = \{a_{ij}\}$	four-pole matrix
$Z = \{z_{ij}\}$	impedance matrix
$T = \{t_{ij}\}$	transmittance matrix