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Methods of near-wall pressure-fluctuation measurements in the presence of vibration

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Abstract

Near-wall pressure fluctuations in turbulent flows are of considerable interest in many engineering applications. We shall concentrate on a number of specific questions related to the resolution of components of wall pressure spectra. Our emphasis shall be on outstanding problems of turbulent pressure fluctuations in the presence of vibration. A study on the interaction of a transducer with wall vibration resulting from near-wall turbulent flows has been performed. Three methods are described for the study of spectral components of turbulent surface pressure in conditions of flow-induced vibration: the method of separation of turbulent and vibration signals; the method of a vibration-proof turbulent pressure transducer; and a modified method of vibration suppression. A method of low-frequency acoustic-noise suppression is also suggested.

1. Introduction

Turbulent pressure fluctuations, which occur in turbulent boundary layers as a result of nonlinear interactions between the eddy field components, are the object of many studies. In fluid mechanics and hydrodynamical acoustics the principal interest in turbulent pressure fluctuations lies in their role as a source of structural excitation and reradiation of acoustic noise. A question of great interest is the effect of vibration and acoustic noise on the measurement of the turbulent pressure fluctuations. The problem of vibration suppression is important for the study of near-wall pressure fluctuations since a miniature piezoelectric sensor not only reacts to turbulent pressure but also generates a signal, which is proportional to the applied force; see, e.g., Willmarth (1975), Blake (1986). In a turbulent flow, the sensor is placed in a zone of intense vibration induced by near-wall pressure fluctuations. In such conditions, piezoelectric sensor transducers are sensitive not only to pressure but acceleration as well. It is therefore necessary to distinguish between turbulent and vibration signals registered by the sensor. The purpose of this communication is to examine three methods for the study of spectral components of turbulent surface pressure in conditions of flow-induced vibration. The three methods are: (i) separation of the turbulent and vibration signals; (ii) vibration-proof turbulent pressure transducer, and (iii) modified method of vibration suppression.

The first method is comparative and is developed on the basis of direct measurement of the vibration spectra; the other methods use the introduction into the transducer of a supplementary element sensitive only to noise and not to pressure fluctuations. Methods of acoustic-noise suppression also are discussed.

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2. Method of separation of turbulent and vibration signals

2.1. Introductory comments

The vibration of a sensor piezo element is among the most common factors hampering the measurement of turbulent pressure. The method of separation of turbulent and vibration signals is based on the direct measurement of the vibration spectra in the vicinity of the pressure fluctuations sensor, determination of equivalent pressure due to vibration, and comparison of the turbulent spectra and the equivalent pressure spectra of vibration noise.

Comparative spectral analysis allows the separation of the turbulent and vibration signals. For a standard miniature vibration-proof turbulent pressure transducer with pressure sensitivity $\gamma_p = 4 \times 10^{-6}$ V/Pa, the value of transducer sensitivity to vibration established in bench-tests was $\gamma_W = 35 \times 10^{-6}$ V/m/s^2.Correct measurements require the essential signal due to the pressure fluctuations to be at least (10) times higher than the noise component (here the vibration component), i.e.,

$$\gamma_P P'/\gamma_W W' \geqslant 10,$$

where P', W' are typical values of measured pressure fluctuations and vibration, respectively. Applied to the above pressure and acceleration sensitivity values γ_P and γ_W, this condition is reduced to

$$\{w'/p'\} \leqslant 10^{-1}\gamma_P/\gamma_W,$$

which cannot always be satisfied.

Typical values of pressure fluctuations P_T and vibration noise for a low-noise wind tunnel are shown on Fig. 1 in dB re: 0.1 Pa for 15 m/s (I), 20 m/s (II), 30 m/s (III), and 0 m/s (IV). The term 'vibration noise' is here taken to represent the signal of the turbulent pressure transducer for a low-noise wind tunnel at flow velocity $V = 0$.

2.2. Separation of the turbulent and vibration signals

An algorithm to estimate the turbulent surface pressure, P_T, in conditions of flow-induced vibration is suggested here. An estimation of the influence of vibration is developed on the basis of direct measurement of the vibration spectra and calculation of the equivalent pressure spectrum, $P_{\text{equivalent}}$ due to the vibration.

An equation for measurement of flow noise, P_{measured}, can be written as

$$P_{\text{measured}} = P_T + P_{\text{equivalent}}. \quad (1)$$

This relation allows us to compare $P_{\text{equivalent}}$ with P_{measured}.

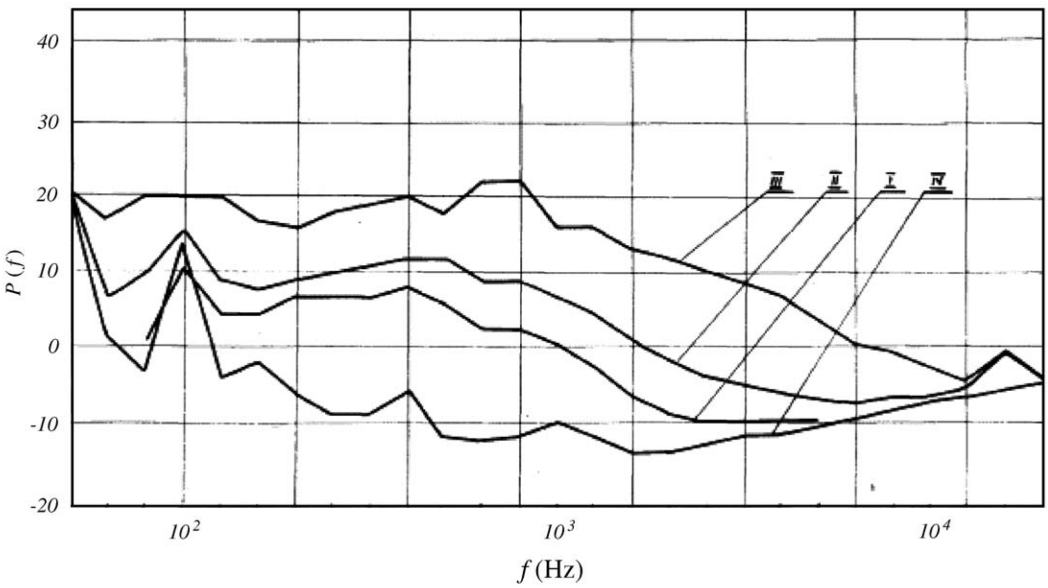

Fig. 1. Wall pressure frequency spectra (in dB re: 0.1 Pa). Flow velocity: (I) = 15 m/s; (II) = 20 m/s; (III) = 30 m/s; (IV) = 0.

The power-spectral density of the transducer signal can be expressed in the form $\Phi(f) = \gamma P(f)$. Here, γ is the sensitivity of the pressure transducer to the measuring parameter and f is frequency. If this definition of the power-spectral density is used, then Eq. (1) takes this simple form

$$\Phi_{\text{measured}}(f) = \Phi_T(f) + \Phi_W(f). \quad (2)$$

The first term represents the contribution of pressure fluctuations P_T. The second term determines the signal produced by the pressure transducer due to vibration.

The term for equivalent pressure in (1) due to vibration can be expressed as

$$P_{\text{equiv}}(f) = \Phi_W/\gamma_P,$$

using the concept of a sensitivity of pressure transducer to measuring parameter.

Direct measurement of vibration by an accelerometer in the vicinity of the pressure fluctuations transducer can define the vibration spectrum $w(f)$:

$$w(f) = \Phi_{\text{acc}}/v(f).$$

Here, Φ_{acc} is the accelerometer signal and v is the sensitivity of the accelerometer to vibration.

The power-spectral density Φ_w of the vibration can be obtained if the vibration spectrum, $w(f)$, is known:

$$\Phi_W(f) = \gamma_W \ \ W(f) = \Phi_{\text{acc}}\,\gamma_W(f)/v(f). \quad (3)$$

The next step in the analysis is the definition the equivalent pressure due to vibration:

$$P_{\text{equiv}}(f) = \Phi_W(f)/\gamma_P = \Phi_{\text{acc}}\gamma_W(f)\big/\gamma_p v(f). \quad (4)$$

Summing these separate contributions gives Eq. (1) for measurements in the form:

$$P_{\text{measured}}(f) = P_T(f) + \Phi_{\text{acc}}\gamma_W(f)/\gamma_P v(f). \quad (5)$$

Fig. 2 shows the results of flow noise measurements in the deep sea. Measurements of wall-pressure were made by us on buoyant units in the Black Sea. The hydrophones were mounted in the buoyant unit body. Using the buoyant units creates an opportunity to make an acoustics-hydrodynamics experiment in a turbulent boundary layer at large values of Re, and in the absence of other noise. Analysis of the measurements in conditions of intensive vibration using Eqs. (4) and (5) shows that the spectral levels of equivalent pressure turn out to be close to the pressure fluctuations level (see Fig. 2). Clearly, the experimental data are contaminated by flow-induced vibration.

The impact of vibration makes it impossible to retrieve turbulent pressure from the measured signal. Various investigators have circumvented this difficulty by measuring the wall turbulent pressure spectrum using unwanted-noise cancellation techniques. This method has been used by Gravante et al. (1998), Farabee and Casarella (1991) and was

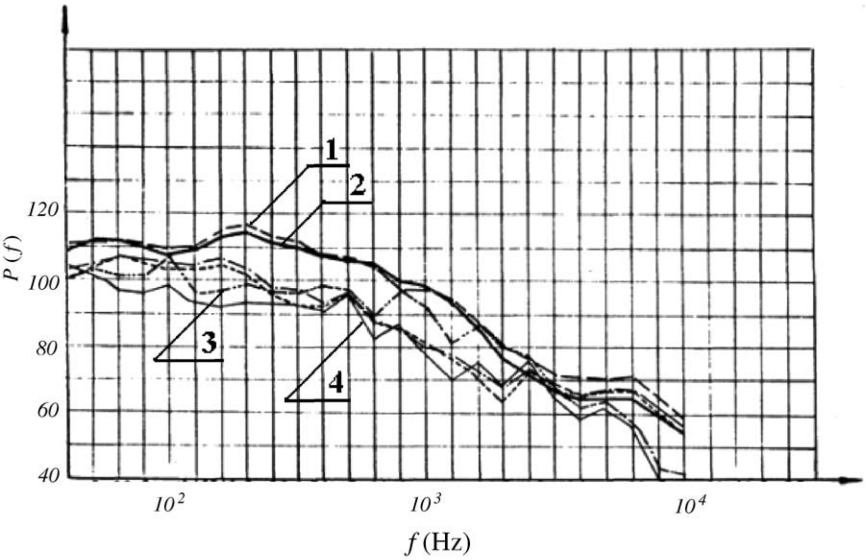

Fig. 2. Comparison of flow noise (in dB re: 0.1 Pa) to equivalent pressure spectrum. Flow velocity = 20.5 m/s: 1 flow noise due of pressure fluctuations; 2 equivalent pressure due to vibration. Flow velocity = 12.4 m/s: 3 Flow noise; 4 equivalent pressure.

first introduced by Wambsganss and Zaleski (1970). The procedures for the utilization of the coherence function to eliminate unwanted signal components from the power-spectral densities of the measured signal have been given in detail by Curling et al. (1992), and Curling and Païdoussis, 1992. Under these conditions, the development of active methods of noise suppression is of special interest.

3. Active vibration suppression methods

Active noise suppression methods are based on introduction into the transducer of a supplementary element, sensitive to noise only but not to pressure fluctuations. Under differential schemes of essential signal determination, a vibration-proportional signal can be deduced if both elements, the main and the supplementary, are switched in the difference mode.

3.1. Method of vibration-proof turbulent pressure transducer

Fig. 3 shows a miniature vibration–proof turbulent pressure transducer on the wall in a low-noise wind tunnel. Sensitive element 2 is mounted inside the transducer block of 4 mm in diameter. Sensitive element 2 is based on a wide-band pressure fluctuations sensor that is a piezoceramic cylinder of 1.3 mm in diameter. Sensor 2 is placed into and fixed hermetically in a brass block 1 shaped into a double-sided glass. The sensitive element 2 receives pressure fluctuations through metallic membrane 4. Compensatory element 3 is made of an identical piezoceramic cylinder, mounted in block 1, so that it is isolated from pressure fluctuations.

Both sensitive elements are switched so that vibration signals are subtracted. Sensor fabrication technology and thorough selection of identical piezoceramic cylinders for sensitive and compensatory elements have a decisive impact on the vibration-proofing of the transducer.

We shall discuss the equations describing the mathematical algorithm for assigning turbulent surface pressure in conditions of flow-induced vibration by a miniature vibration–proof turbulent pressure transducer in Section 4. The characteristics of a vibration-proof turbulent pressure transducer were considered before, e.g. Kudashev (2003). The efficiency of vibration suppression has been demonstrated (see Fig. 4) both in bench-tests of sensitive elements and in miniature vibration-proof transducers while using them for turbulent pressure investigation in boundary layers and jet flow.

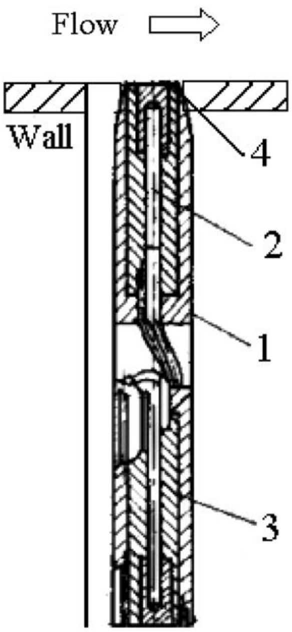

Fig. 3. Vibration-proof turbulent pressure transducer on the wall in a low-noise wind tunnel. 1. Transducer block; 2. sensor; 3. supplementary element; 4. membrane.

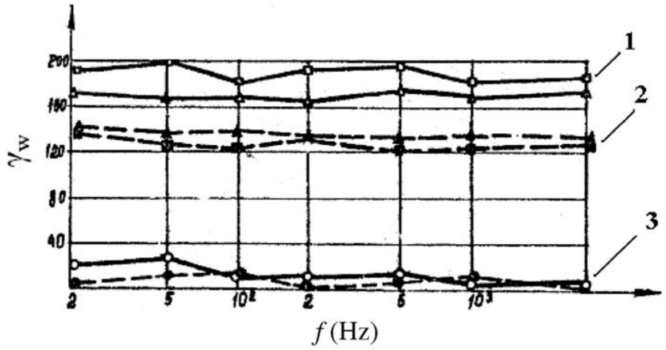

Fig. 4. Vibration sensitivity of turbulent pressure transducer (in dB re: V/m/s^2): 1 and 2. sensitive elements for sensors; 3. vibration-proof transducers.

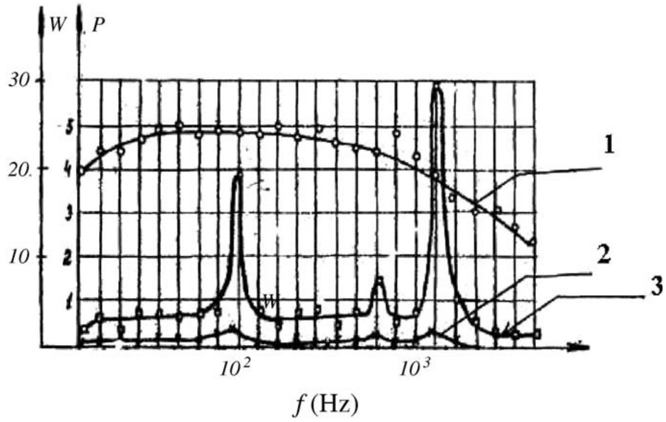

Fig. 5. Measured frequency spectra at the wall in a low-noise wind tunnel(in dB re: 0.1 Pa): 1. pressure fluctuations; 2. the wind tunnel noise (flow velocity = 0); 3. vibration measurements.

Bench-tests of miniature vibration-proof sensors have proven that their sensitivity to vibration is 5–10 times less than the vibration sensitivity of wide-band transducers without compensation.

3.2. Typical results

Results of an experimental measurement in a low-noise wind tunnel (see Fig. 5) show that the vibration–proof piezoelectric transducer developed by the author assures vibration suppression in conditions of intense vibration noise.

Another example of using the miniature vibration-proof sensors by Andreev and Veip, 1980. is shown in Fig. 6. The outer scale, δ^*, is the displacement thickness, τ_W is the mean wall-shear stress, V_∞ is the free-stream velocity, f^* is the frequency normalized with the outer timescale, $f\delta^*/V_\infty$.

Presentation of the results of experiment (Fig. 6(a)), in dimensionless form as dependence on the dimensionless performance $P^* = \left(P^2/\tau_W^2\right)\left(V/\delta^*\right)$ of dimensionless frequency $f^* = f\delta^*/V_\infty$, provides the approximation of the wall-pressure spectrum measurements on the flow velocity $V_1 = 4.5\,\mathrm{m/s}$, $V_2 = 3.5\,\mathrm{m/s}$, $V_3 = 2.5\,\mathrm{m/s}$, as an unified curve (see Fig. 6(b)). Hydrodynamic normalization of the outer scales τ_W and δ^* can serve as a criterion of correctness for pressure fluctuation measurements.

4. Vibration suppression methods using mean-square noise

There exists a condition of coherent noise influence on the main and compensatory sensitive elements limiting the use of vibration-proof sensors. These transducers, employing the technique of active compensation on instantaneous noise values, are effective provided that the main and compensatory elements are subject to a coherent vibration influence.

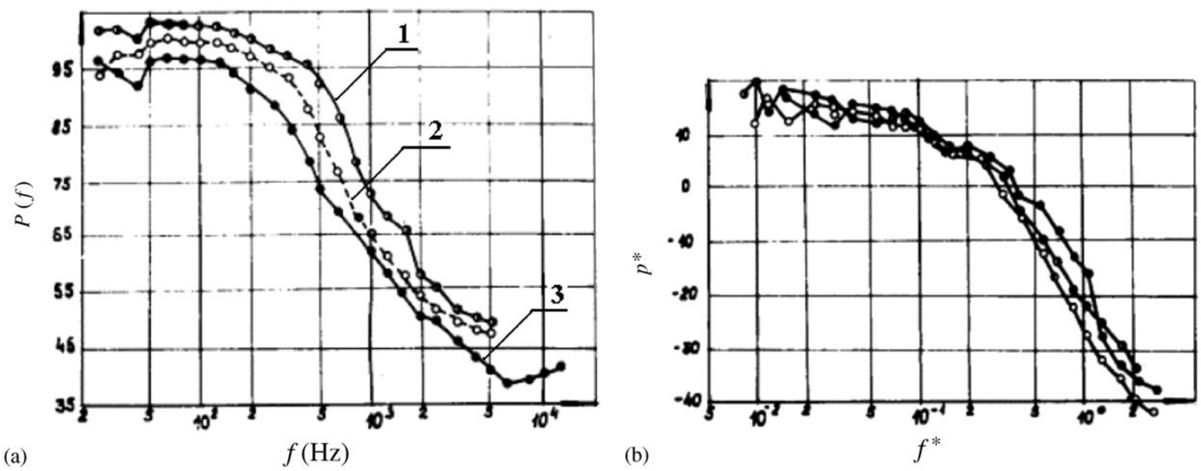

Fig. 6. Wall pressure spectrum (in dB re: 0.1 Pa). measured by miniature vibration-proof turbulent pressure transducers. Flow velocity: 1. 4.5 m/s; 2. 3.5 m/s; 3. 2.5 m/s. (a) Frequency f (Hz), (b) Frequency $f^* = f\delta^*/V_\infty$.

The scales of vibration field are determined by the lengths of the deformation waves induced in the device by vibration in the absence of flow. These scales significantly exceed the distance between the main and compensatory elements of sensor.

These methods are effective if there is no possibility of ensuring vibration signal phase matching of the main and compensatory elements. Methods for the registration of near-wall turbulent pressure fluctuations weakly correlated with vibration impact on piezoelectric sensors employ the large difference between the spatial scales of turbulent heterogeneities and the noise field.

Strong multi-mode vibration often occurs in engineering installations, power machines and devices. At high frequencies, the contribution of small-scale components into vibration noise becomes significant. In this case, phase matching of vibration signals cannot be assured, and thus the coherence condition of noise impact on the main and the compensatory sensitive elements is violated.

Generally speaking, instantaneous vibration signals from the main and compensatory sensitive elements are different, since instantaneous loads due to vibration are not the same. Therefore, when eliminating noise, one should very cautiously use the vibration bench-test results for vibration-proof transducers because the impact of mutual disposition of the main and compensatory elements must be taken into consideration. Our work (Kudashev, 2003) shows that in this case it is reasonable to use the mean square vibration suppression method. In this section, an algorithm is suggested to separate turbulent pressure from vibration background in conditions when the major part of vibration is correlated with the studied turbulent pressure fluctuations.

The output signal of the main sensitive element of vibration-proof turbulent pressure transducer may be written as

$$U_1(t) = \int K(\boldsymbol{x})p(\boldsymbol{x},t)\,\mathrm{d}\boldsymbol{x} + \int L_1(\boldsymbol{x})p(\boldsymbol{x},t)\,\mathrm{d}\boldsymbol{x} + W_1(t). \tag{6}$$

The first term represents the contribution of pressure fluctuations p ($\boldsymbol{x}$, t) only at the transducer sensor plate. The second term determines the signal produced due to deformation of the streamlined body caused by near-wall pressure fluctuations in the vicinity of the point of measurement outside the sensitive element. The last term, $W_1(t)$ in Eq. (6), represents a "pure vibration" signal, that is the signal due to "far vibration" which is not connected to pressure fluctuations in the zone of measurement. Functions $K(\boldsymbol{x})$ and $L_1(\boldsymbol{x})$ schematically shown in Fig. 7, determine the response of the main sensitive element 1 to point excitation at point $\boldsymbol{x}$ in the pressure fluctuations measurement zone for $K(\boldsymbol{x})$, and outside the sensor plate for $L_1(\boldsymbol{x})$.

By analogy with (6), the signal generated by the compensatory sensitive element of a transducer may be written as

$$U_2(t) = \int L_2(\boldsymbol{x})p(\boldsymbol{x},t)\mathrm{d}\boldsymbol{x} + W_2(t), \tag{7}$$

where L_2 is the response of the sensitive element to point excitation outside the sensor plate (relative vibration sensitivity).

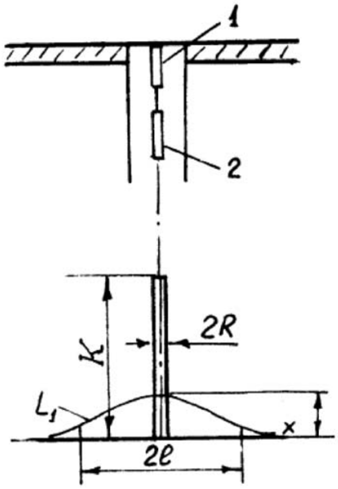

Fig. 7. Model of vibration-proof turbulent pressure transducer: 1. main sensitive element; 2. compensatory sensitive element.

Under full compensation of the "pure vibration" signal, i.e. when $W_1 = W_2$, the resulting signal of vibration–proof turbulent sensor takes the form

$$U(t) = U_1(t) - U_2(t) = \int [K(\mathbf{x}) + L_1(\mathbf{x}) - L_2(\mathbf{x})]p(\mathbf{x}, t)\mathrm{d}\mathbf{x}. \tag{8}$$

It is obvious from the last equation that the vibration due to the deformation of the wall caused by near-wall pressure fluctuations beyond the vicinity of the measurement point produces a significant effect on the resolution capability of a turbulent pressure fluctuations sensor. As demonstrated by Kudashev (2003), expressions for the spectra of the signals measured in experiments using pressure fluctuations sensors of different types are given based on Eq. (8).

Estimates of vibration effect are made in for a miniature vibration-proof turbulent pressure sensor with a round sensitive plate. Suppose the response of the sensitive element to point excitation is

$$K = \gamma/\pi R^2, \quad |\mathbf{x}| \leqslant R.$$

Let the function of the sensor local sensitivity to "far" pressure fluctuations, that is fluctuations outside the sensitive element of the sensor, be

$$L_1(x) = aK \exp\left\{-\left(l/R\right)^2\right\}.$$

For miniature vibration-proof transducers whose compensatory element is sunk with respect to the streamlined surface (Fig. 7), local vibration sensitivity L_2 converges to zero. Then we can disregard the effect of pressure fluctuations on signal U_2 of the compensatory element in the measurement zone.

From comparison of the signal spectral density of a vibration-proof sensor, we have

$$\Phi_{UU}(\omega) = \gamma^2 \int\int \left[1 + a\left(l/R\right) \exp\left\{-\left(kl/2\right)^2\right\}\right]^2 E_{PP}(\mathbf{k}, \omega)\, \mathrm{d}\mathbf{k} \tag{9}$$

and the expression for the frequency spectrum of the turbulent pressure fluctuations is given by

$$\Phi_{PP}(\omega) = \gamma^2 \int\int E_{PP}(\mathbf{k}, \omega)\, \mathrm{d}\mathbf{k}.$$

Here, $\mathbf{k} = (k_1, k_2)$ is the wavenumber vector. It is evident that the vibration due to the near-wall pressure fluctuations introduces an extra error to the turbulent pressure measurement.

Besides the turbulent pressure frequency wave spectrum, $E_{PP}(\mathbf{k}, \omega)$, the signal registered by a vibration-proof turbulent pressure transducer is also affected by transducer construction parameters such as the relative vibration sensitivity $a = L_{1\max}/K_{\max}$, and the ratio of the sensitive plate radius R to the *effective* radius of the zone of *outside* pressure fluctuations impact l. These are the parameters in (9) that take into account the properties of the construction and mutual disposition of the main and compensatory elements of a turbulent pressure transducer. The properties of the frequency–wave spectrum, $E_{PP}(k, \omega)$, have been detailed by Maidanik and Jorgensen (1967), Kudashev and

Yablonik (1977). For the present paper, the main interest in the frequency–wave spectrum is in the character of the energy distribution of the two-dimensional field of near-wall pressure over spatial scales λ_T and phase velocities $V = \omega/k$.

5. Modified method of active vibration suppression

The vibration suppression method may turn out to be inefficient if the relative vibration sensitivity is too big or the *outside* pressure fluctuation zone is too small: $1 \ll \lambda_T$. In order to raise the resolution capability of turbulent pressure sensor in these conditions, this paper suggests and discusses methods of active vibration suppression employing an array of sensitive elements incorporated in a turbulent pressure sensor. Besides the main sensitive element, the modified measuring complex comprises the array of two supplementary sensitive elements, placed near the streamlined surface symmetrically on both sides of the main element at a distance d to it (Fig. 8). The supplementary elements are switched sequentially to each other and towards the main sensitive element.

When the sizes, R, of turbulent pressure fluctuations sensors are small and the distance between them in the array is small too: $d \sim R$, the signal spectrum of the vibration-proof complex is written as

$$\Phi_{UU}(\omega) = \gamma^2 \int\int \left[1 + \tfrac{1}{2}a(d/R)^2 (k_\gamma l)^2 \exp\{-(kl/2)\}\right]^2 E_{PP}(\boldsymbol{k}, \omega)\, \mathrm{d}\boldsymbol{k}. \tag{10}$$

Here, k_λ is a projection of the vector $\boldsymbol{k}$ on the plane of the array.

In the modified vibration-proof measurement complex, the relative influence of vibration due to the excitation of vibration by pressure fluctuations is limited by the value of the order of vibration sensitivity a. Such level of vibration, as a rule, is acceptable for adequate measurement of turbulent pressure fluctuations, as demonstrated by Kudashev and Yablonik, 2002.

6. Low-frequency acoustic noise suppression

Experimental data are usually contaminated by facility-related noise in the low-frequency range. Acoustic noise is considered to be the extraneous contribution to the frequency spectrum at low frequencies. In low-speed wind tunnel

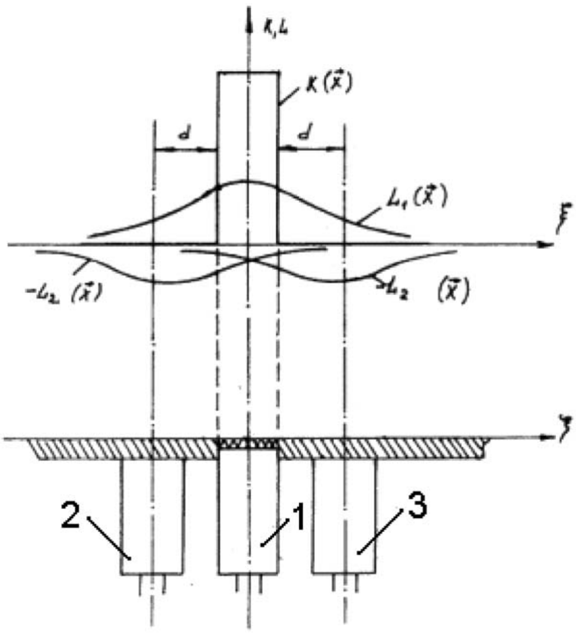

Fig. 8. Model of vibration-proof turbulent pressure transducer: 1. main element of pressure transducer; 2 and 3. array of supplementary elements.

measurements, pressure fluctuations appears to arise in the wind-tunnel diffuser and to travel upstream as acoustic waves [see, e.g., Blake (1986), Blake and Chase, 1971]. The difficulty of turbulent pressure fluctuations measurement arises because a pressure transducer cannot distinguish between turbulent eddies and acoustic waves. Currently, noise cancellation techniques are used as a way of obtaining uncontaminated wall pressure measurements by other researchers, e.g., Wambsganss and Zaleski (1970), Farabee and Casarella (1991), Gravante et al. (1998). Frequency spectral data usually utilize (passive) noise cancellation techniques.

The low-frequency acoustic-noise suppression method for measurement of turbulent pressure fluctuations is based on comparison of the spatial scales of turbulent pressure and the noise field. The spatial scales of turbulent pressure fluctuations and acoustic noise are shown on Fig. 9.

The wavenumber spectrum, $E(\boldsymbol{k}, \omega)$, of near-wall turbulent pressure field (Fig. 10) makes a sum of spatial spectra of turbulence(T) and vibration noise (N):

$$E_{PP}(\boldsymbol{\kappa}, \omega) = E^{T}_{PP}(\boldsymbol{\kappa}, \omega) + E^{T}_{PP}(\boldsymbol{\kappa}, \omega). \tag{11}$$

it is noted that both $\boldsymbol{\kappa}$ and $\boldsymbol{k}$ denote the wavenumbers.

Fig. 11 shows an acoustic-noise–proof pressure fluctuations transducer providing the noise suppression of low-frequency components in measurements of turbulent pressure fluctuations.

Fig. 12 shows the filter functions $S(\boldsymbol{k})$ of an acoustic-noise–proof pressure fluctuations transducer for main element 1 of the sensor and for supplementary element 2 of the sensor. The resulting signal of the acoustic noise-proof turbulent sensor can be written as

$$S(t) = \int [K_1(\boldsymbol{x}) - K_2(\boldsymbol{x})] p(\boldsymbol{x}, t)\, d\boldsymbol{x}. \tag{12}$$

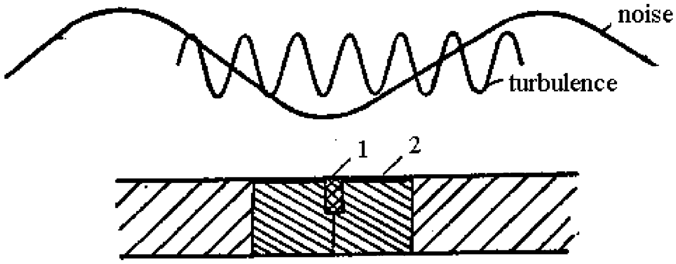

Fig. 9. Spatial scales of turbulent pressure fluctuations and acoustic noise. 1. Main element of acoustic-noise-proof pressure transducer, sensitive to noise and to pressure fluctuations; 2. supplementary element of transducer, sensible to noise only bit not to pressure fluctuations.

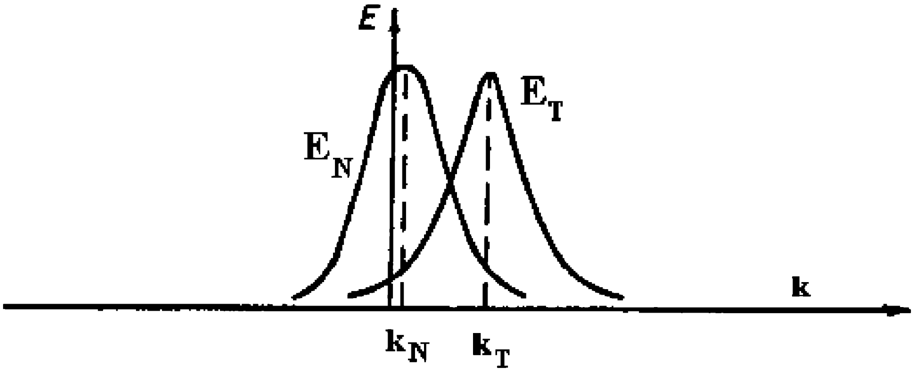

Fig. 10. Wave-number spectrum of turbulence (T) and acoustic noise (N). Scale of turbulence: $l_T \sim \frac{1}{k_T}$; Scale of noise: $l_N \sim \frac{1}{k_N}$.

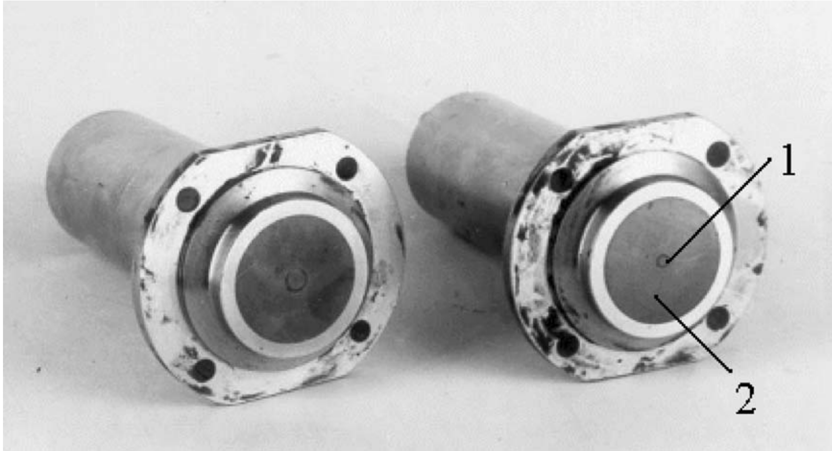

Fig. 11. Acoustic noise-proof turbulent sensors. 1. Main element of pressure transducer sensitive to acoustic noise and to pressure fluctuations; 2. supplementary element of transducer, sensitive to noise only but not to pressure fluctuations.

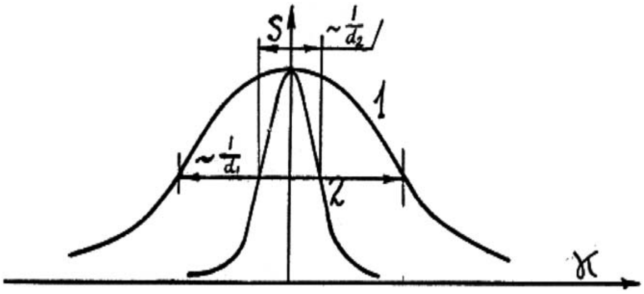

Fig. 12. The filter function $S(\boldsymbol{\kappa})$ of acoustic-noise-proof pressure fluctuations transducer. 1. Main element of pressure transducer sensitive to noise and to pressure fluctuations; 2. supplementary element of transducer, sensitive to noise only but not to pressure fluctuations.

Let the function $K_1(\boldsymbol{x})$ for circle sensors be:

$$K_1(\boldsymbol{x}) = \begin{cases} \gamma/\pi R_1^2 .... |\boldsymbol{x}| < R_1, \\ 0 .... |\boldsymbol{x}| \geqslant R_1; \end{cases}$$
$$K_2(\boldsymbol{x}) = \begin{cases} \gamma/\pi R_1^2 .... |\boldsymbol{x}| < R_2, \\ 0 .... |\boldsymbol{x}| \geqslant R_2. \end{cases} \quad (13)$$

Here is $K(\boldsymbol{x}) = K_1(\boldsymbol{x}) - K_2(\boldsymbol{x})$ determines the response of the sensitive elements 1 and 2 to point excitation.

The wave-number function of a sensor may thus be written as

$$K(\kappa) = K_1(\kappa) - K_2(\kappa) = \gamma \left[\frac{J_1(\kappa R_1)}{\kappa R_1/2} - \frac{J_1(\kappa R_2)}{\kappa R_2/2} \right], \quad (14)$$

where J_1 denotes the Bessel function of the first kind and order 1.

Using the condition $S(\boldsymbol{\kappa}) = |K(\boldsymbol{\kappa})^2|$, the filtering function of sensor can be written on the basis of Eq. (14) as:

$$S(\kappa) = \gamma^2 \left(\frac{2J_1(\bar{\kappa})}{\bar{\kappa}} \right)^2 \left[1 - \frac{\alpha J_1(\bar{\kappa}/\alpha)}{J_1(\bar{\kappa})} \right]^2, \quad (15)$$

where $\bar{\kappa} = K/R$ and $\alpha = R_1/R_2$, i.e., α is the diameter ratio for sensitive elements 1 and 2.

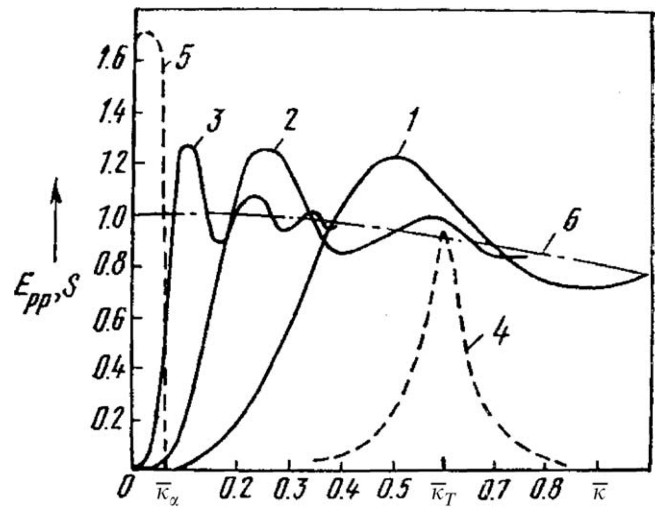

Fig. 13. Filtering action of transducer to acoustic noise excitation. 1–3. The filtering functions of sensor $S(\boldsymbol{k})$ for diameter ratio $\alpha = 1{:}10$; 1:20; 1:50; 4. wavenumber-frequency spectrum E_{pp} of turbulent pressure; 5. wavenumber-frequency spectrum E_{pp} of acoustics noise; 6. the filtering functions of sensor $S(\boldsymbol{k})$ for single transducer.

The signal spectrum of the acoustic-noise-proof transducer on the base (11) and (15) becomes

$$\Phi_{ss}(\omega) = \int_{\infty} S(\kappa) E_{pp}(\kappa, \omega)\, \mathrm{d}\kappa. \tag{16}$$

The result of the numerical analysis, Eq. (16), shows that the best suppression of acoustic noise will be in the case of:

$S(\boldsymbol{\kappa}) = 0, \quad \bar{\kappa} \leqslant \bar{\kappa}_{ak}$, the field of noise excitation, and

$S(\boldsymbol{\kappa}) = \text{const}, \quad \bar{\kappa} > \bar{\kappa}_{ak}$

The filtering action of an acoustic-noise-proof pressure fluctuations transducer is shown in Fig. 13, where in the acoustic-noise–proof pressure fluctuations transducer is presented as a wave-number filter: see curves 1–3 of the filtering functions $S(\boldsymbol{\kappa})$ of the sensor. The result of a numerical simulation has shown that acoustic-noise suppression can be provided by a turbulent pressure transducer.

The conditions for acoustic-noise suppression were obtained: (i) the transducer diameter ′ ratio $\alpha = 1:20$ for main element of pressure transducer to supplementary element; (ii) Mach number $M \leqslant 0.1$; (iii) Strouhal number range: $0.2 \leqslant \omega R_1/v \leqslant 0.8$; (iv) frequency range: 750–3000 Hz.

7. Conclusion

This investigation presents the experimental method for the accurate measurement of near-wall pressure fluctuations in turbulent flows in conditions of flow-induced vibration.

The problem of vibration suppression is important for the study of near-wall pressure fluctuations since a miniature piezoelectric sensor not only reacts to turbulent pressure but also generates a signal that is proportional to the applied force. The approach taken in this investigation is based on exploitation of active methods to correct measured spectra for interference from unwanted effects. Three methods are described for the study of spectral components of turbulent surface pressure in conditions of flow-induced vibration: the method of separation of turbulent and vibration signals; the method of vibration-proof turbulent pressure transducer; and a modified method of vibration suppression. The examples show that the methods work, and that it is possible to distinguish between turbulent and vibration signals registered by the sensor.

The other purpose of this paper was to provide a method of determining the turbulent wall-pressure spectra in the presence of possible contamination of the measurement by spurious background acoustic noise or noise associated with the turbulent boundary layer. We focus attention on the case when the pressure transducer cannot distinguish between turbulent eddies and acoustic waves. Our key interest here was to provide the noise suppression of low frequency components when measuring turbulent pressure fluctuations. Noise cancellation techniques based on spatial filtering are used as a way of obtaining uncontaminated wall pressure measurements in the low-frequency range. The results of numerical analysis show acoustic-noise–proof pressure fluctuations transducers act as a wavenumber filter. The filtering action of a transducer to acoustic-noise excitation is obtained. The best suppression of acoustic noise was realized in the case of low frequency components of acoustic noise.

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