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VIBRATION-PROOF SYSTEMS OF HYDROPHYSICAL VELOCITY FIELD SENSORS IN THE CONTOUR OF A CIRCULAR CYLINDER

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Abstract

Vibration-proof systems of three flush-mounted tangent flow velocity sensors installed on the surface of a rigid circular cylinder are considered. Three variants of the sensor disposition, namely on one, two and three circles, the sections of the cylinder, are studied. The corresponding algorithms for coprocessing the signals of individual sensors are designed. The experimental results are presented for validation of the theoretical conclusions.

INTRODUCTION

Low frequency vibration is a source of noise disturbances distorting the signals of hydrophysical velocity field sensors mounted on moving apparatus. The physical reason of this phenomenon lies in the impossibility to separate two additive components in the observable signal of an individual sensor. The first one is a friendly signal caused by the turbulent flow velocity fluctuations, the second component is a parasite caused by the sensor oscillations relative to the fluid.

This work extends the theoretical and experimental investigations of the sensor systems immune to vibrations of the system carrier [1-3]. The output signal of such system is a linear combination of the individual sensor signals. The combination coefficients depend on (i) the number of the vibrating sensors, and (ii) the sensor three-dimensional configuration. In the present paper, the systems of three conformal (flush-mounted) tangent flow velocity sensors installed on the surface of a rigid circular cylinder are considered. The sensitivity axes of all three sensors are directed along the tangents to the circles, the sections of the cylinder.

THREE SENSORS ON ONE CIRCLE

Let S be an output signal of the system of three flush-mounted hydrophysical velocity field sensors installed on one circle, the section of a rigid cylinder:

$$S = S_1 + a_2 S_2 + a_3 S_3 . \qquad (1)$$

Here S_i , $i = 1,2,3$, are the signals of individual sensors. It is shown that S is insensitive to the vibration of the cylinder if the coefficients a_2 and a_3 satisfy a system of equations

$$\begin{cases} sign\varphi_1 + a_2 sign\varphi_2 + a_3 sign\varphi_3 = 0; \\ \cos\varphi_1 sign\varphi_1 + a_2 \cos\varphi_2 sign\varphi_2 + a_3 \cos\varphi_3 sign\varphi_3 = 0; \\ \sin\varphi_1 sign\varphi_1 + a_2 \sin\varphi_2 sign\varphi_2 + a_3 \sin\varphi_3 sign\varphi_3 = 0; \end{cases} \qquad (2)$$

where

$$sign\varphi = \begin{cases} +1; \varphi > 0 \\ -1; \varphi < 0 \end{cases} . \qquad (3)$$

An angle φ is counted out from the negative direction of the axis x (Figure 1). The angle $\varphi = 0$ is excluded from consideration. The magnitudes a_2 and a_3 have the following physical meaning. If the values a_2 and a_3 satisfy system of equations (2), then linear combination (1) does not depend on time and is equal to zero,

$$S = 0 , \qquad (4)$$

for an arbitrary motion of the cylinder in a motionless fluid (in other words, in the absence of turbulence in the fluid).

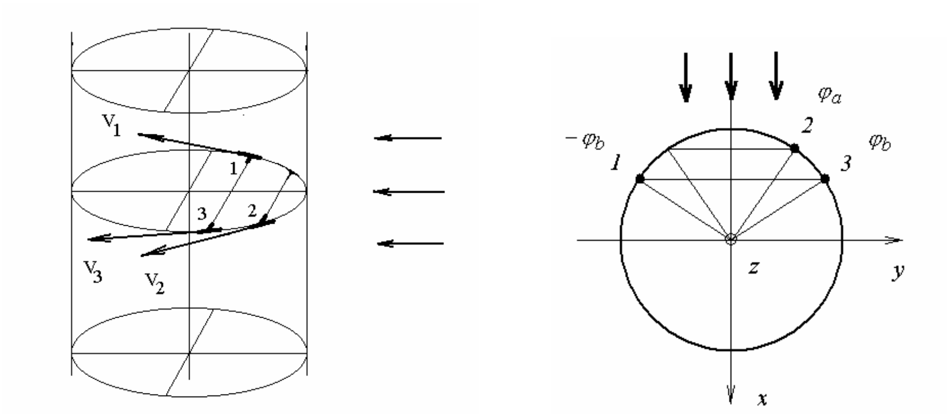

Figure 1 – One of the variants of the three sensor disposition on the surface of a circular cylinder (left) and its schematic representation (right)

The first equation of system (2) means the insensitivity of S to ω_z that is to rotational vibrations of the cylinder around its axis z. The second and third equations of (2) mean the insensitivity of S to U_y and U_x that is to translational vibrations of the cylinder along the axes y and x respectively. In general, set (2) of three equations with two unknown quantities has no solution. From a physical viewpoint, the absence of solution means the impossibility to compensate simultaneously the noise disturbances caused by all vibrational degrees of freedom of a rigid cylinder. If, however, we neglect any one of three above mentioned degrees of freedom (that is if we simplify the vibrational mode under consideration), the number of equations decreases by unity, and we obtain a system of two equations with two unknowns.

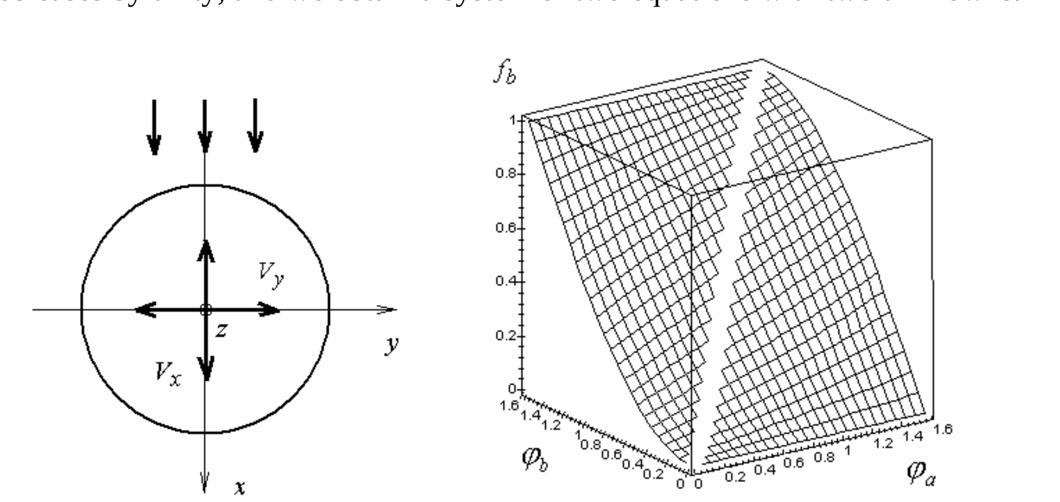

Figure 2 – Schematic representation of a cylinder vibratory motion corresponding to two translational degrees of freedom (left), and relative contribution of rotational vibrations around the cylinder axis z to the output signal of the sensor system as a function of the sensor disposition (right)

For example, the degenerate system of equations characterizing the simplified vibrating mode presented in Figure 2 (left) takes the form:

$$\begin{cases} \cos\varphi_1 sign\varphi_1 + a_2\cos\varphi_2 sign\varphi_2 + a_3\cos\varphi_3 sign\varphi_3 = 0; \\ \sin\varphi_1 sign\varphi_1 + a_2\sin\varphi_2 sign\varphi_2 + a_3\sin\varphi_3 sign\varphi_3 = 0; \end{cases} \quad (5)$$

It can easily be checked that equations set (5) has the following solution:

$$\begin{cases} a_2 = \dfrac{\sin(2\varphi_b)}{\sin(\varphi_b - \varphi_a)} \\ a_3 = -\dfrac{\sin(\varphi_b + \varphi_a)}{\sin(\varphi_b - \varphi_a)} \end{cases} \quad (6)$$

The value of a vibrational disturbance caused by a “nonexcluded” degree of freedom depends on two factors: (i) an arrangement of three sensors, and (ii) an intensity of appropriate (disregarded) vibration. If we use the coprocessing algorithm corresponding to the vibrating mode presented in Figure 2 (left), then the contribution of rotational vibration to the instantaneous value of an output signal of the three sensor system can be written as

$$S^{(\omega_z)} = -2k_s\omega_z R \cdot f(\varphi_a, \varphi_b), \tag{7}$$

where

$$f(\varphi_a, \varphi_b) = f_b = \sin\varphi_b \frac{\cos\varphi_a - \cos\varphi_b}{\sin(\varphi_b - \varphi_a)}. \tag{8}$$

Here k_s is the conversion coefficient of the sensor, ω_z is the instantaneous value of the angular velocity, R is the cylinder radius. Using expressions (7), (8) and Figure 2 (right) it is easy to estimate quantitatively the degree of the vibrational disturbance suppression.

The processing of the experimental data has shown an increase in the efficiency of the turbulent area indication in conditions of the vibrational noise disturbances on the basis of an output signal of the sensor system compared to the turbulent area indication on the basis of the signals of individual sensors. The appropriate records are represented in Figure 3. In this figure, two turbulent areas correspond to the argument ranges 131000-135000 and 163000-167000.

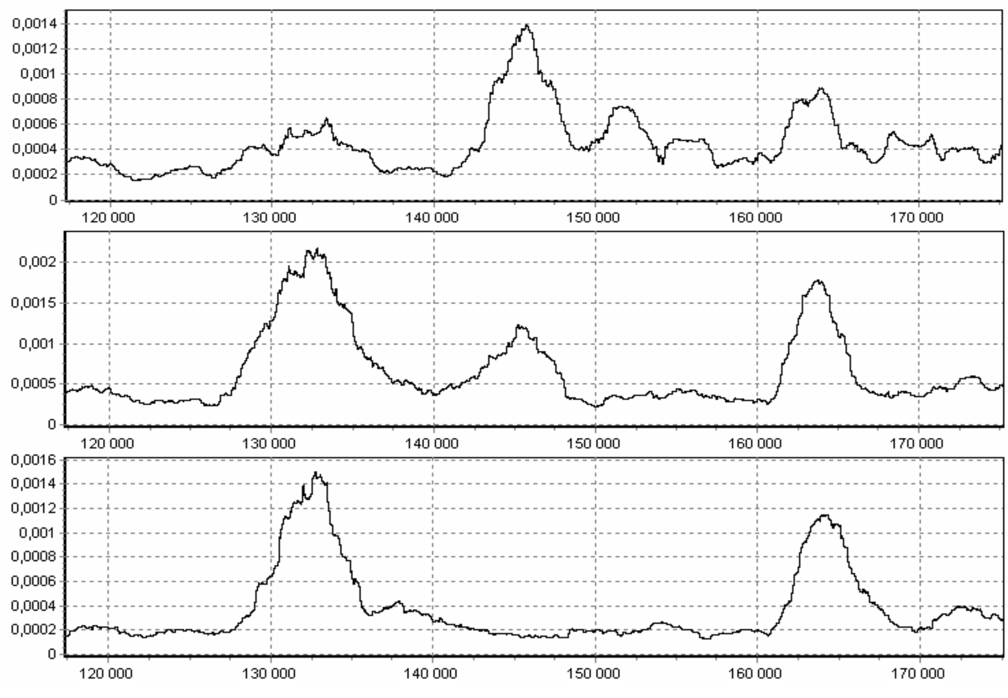

Figure 3 – Presentation of two turbulent areas using various signals: the signal of an individual sensor, the signal of a three-sensor system, and the output signal of a complete vibration-proof four-sensor system (top-down)

The signal coprocessing in the system of three sensors installed on the cylinder surface was made in accordance with algorithm {(1), (6)}. The indication of turbulent areas was carried out by registration of an excess of the current value of a fluctuation intensity over certain threshold. To determine the intensity of fluctuations, the variance of the appropriate signal in the certain frequency band was calculated. Clearly, the best contrast of the turbulent areas takes place in the signal of a complete vibration-proof system formed by four sensors in the contour of the cylinder (Figure 3).

THREE SENSORS ON TWO CIRCLES

In the general case, the set of equations describing the properties of a system of three velocity field sensors disposed on the surface of a circular cylinder, the sensor sensitivity axes being oriented along the tangents to the circles, the sections of the cylinder, has the form

$$\begin{cases} \sin\varphi_1 sign\varphi_1 + a_2\sin\varphi_2 sign\varphi_2 + a_3\sin\varphi_3 sign\varphi_3 = 0; \\ \cos\varphi_1 sign\varphi_1 + a_2\cos\varphi_2 sign\varphi_2 + a_3\cos\varphi_3 sign\varphi_3 = 0; \\ sign\varphi_1 + a_2 sign\varphi_2 + a_3 sign\varphi_3 = 0; \\ z_1\cos\varphi_1 sign\varphi_1 + a_2 z_2\cos\varphi_2 sign\varphi_2 + a_3 z_3\cos\varphi_3 sign\varphi_3 = 0; \\ z_1\sin\varphi_1 sign\varphi_1 + a_2 z_2\sin\varphi_2 sign\varphi_2 + a_3 z_3\sin\varphi_3 sign\varphi_3 = 0; \end{cases} \quad (9)$$

System of equations (2) considered in the previous section is an extreme case of system of equations (9) when all three sensors are disposed on one circle. Two another particular cases are the sensor disposition on two and three circles. In the present paper, six variants of the three sensor disposition on two circles are considered. They are schematically represented in Figure 4. One of the variants, namely the sensor configuration *2a*, is shown in Figure 5 (left).

A set of equations with two unknowns a_2 and a_3 has a solution if the number of equations is equal to two. There exist two "mechanisms" for reduction of the number of equations in system (9). The first one is a "natural" degeneration of the set as a result of the special arrangement of the sensors. In this situation, the number of the vibrational degrees of freedom we take into account does not reduce. Here the influence of all vibrational degrees of freedom is compensated in the system output signal S. In the second case, some equation are "artificially" excluded from consideration, this means physically that we neglect the corresponding vibrational degrees of freedom. It is obvious that here only the influence of nonexcluded vibrational degrees of freedom is compensated in the output combination signal.

It is shown that in all considered variants of the three sensor disposition on two circles the influence of two or three vibrational degrees of freedom remains uncompensated. Consequently, the three sensor disposition on two circles has no advantage over the sensor disposition on one circle.

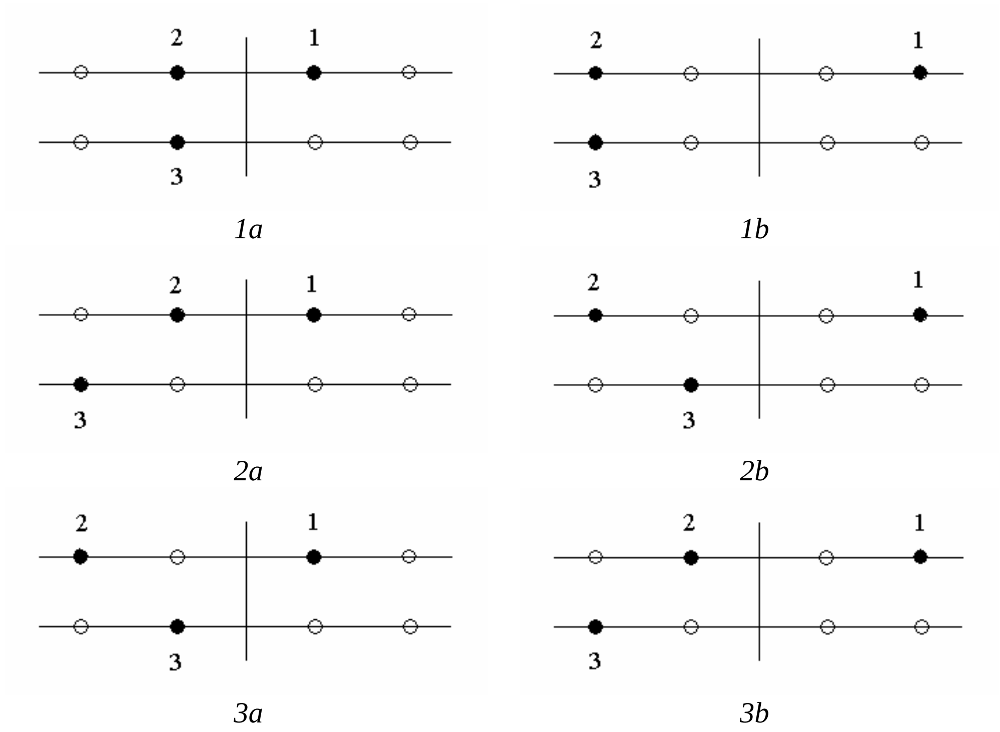

Figure 4 – Schematic representation of six variants of the three sensor disposition on two circles on four generatrices of a circular cylinder

THREE SENSORS ON THREE CIRCLES

Consider the three sensor disposition presented in Figure 5 (right). For the sensors disposed on one generatrices of the cylinder we have

$$\varphi_1 = \varphi_2 = \varphi_3 \equiv \varphi_{1,2,3}; \qquad (10)$$

$$sign\varphi_1 = sign\varphi_2 = sign\varphi_3 = sign\varphi_{1,2,3}; \qquad (11)$$

It can easily be checked that system of five equations (9) degenerates then to the set of two equations

$$\begin{cases} 1 + a_2 + a_3 = 0; \\ z_1 + a_2 z_2 + a_3 z_3 = 0; \end{cases} \qquad (12)$$

This system of equations has the following solution:

$$\begin{cases} a_2 = -\dfrac{z_3 - z_1}{z_3 - z_2}; \\ a_3 = \dfrac{z_2 - z_1}{z_3 - z_2}; \end{cases} \tag{13}$$

In this case, the sensors form a complete vibration-proof system insensitive to all six vibrational degrees of freedom of the cylinder. The output signal of the sensor system has the form (1):

$$S = S_1 - \frac{z_3 - z_1}{z_3 - z_2} S_2 + \frac{z_2 - z_1}{z_3 - z_2} S_3 \ . \tag{14}$$

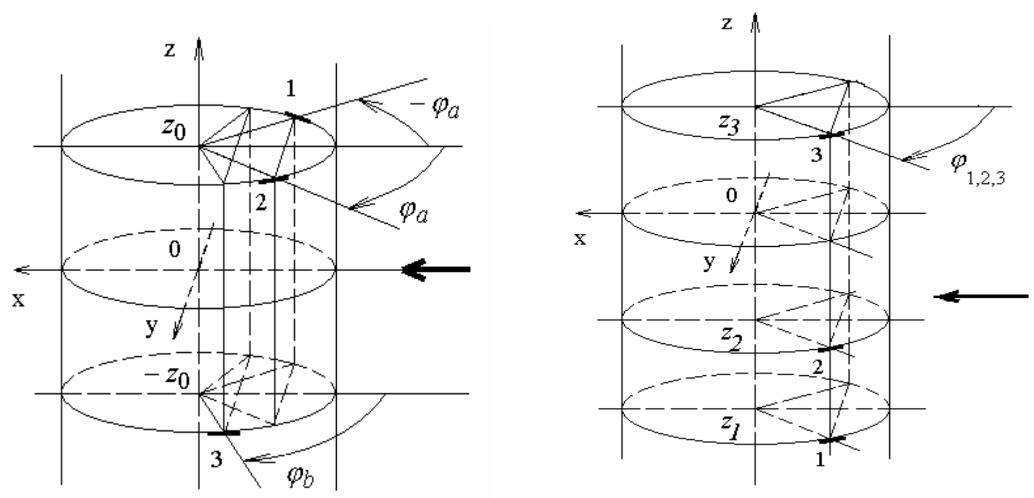

Figure 5 – Two particular cases of the three sensor possible disposition on the surface of a circular cylinder: on two circles (left) and on three circles (right)

Evidently, the following expressions for the equidistant arrangement of three sensors on one generatrix are valid:

$$z_3 - z_2 = z_2 - z_1 = \frac{1}{2}(z_3 - z_1) \ . \tag{15}$$

For such sensor system the algorithm of signal coprocessing has the simplest form:

$$S = S_1 + S_3 - 2S_2 \ . \tag{16}$$

Finally, note two specific features of the expressions for the signal S obtained in this section. First of all, these expressions coincide with the algorithm of the signal coprocessing for the complete vibration-proof system of three traditional (nonconformal) sensors arranged equidistantly on one straight line. Further, expressions (14) and (16) are valid not only for the circular cylinder but also for cylinders of other shape if the sensors are disposed on one generatrix.

SUMMARY

The main results can be summarized as follows.

The system of three flush-mounted hydrophysical velocity field sensors installed on one circle, the section of a circular cylinder, allows to compensate the noise disturbances induced by five of six vibrational degrees of freedom of the cylinder.

The disposition of three sensors on two circles, the sections of a circular cylinder, is less effective method (in comparison with the sensor disposition on one circle) because in this case the influence of two or three (instead of one) vibrational degrees of freedom remains uncompensated.

Three conformal sensors form a complete vibration-proof system if the sensors are disposed on one generatrix of a cylinder. Such sensor system allows to compensate the noise disturbances induced by all six vibrational degrees of freedom of a rigid cylinder.

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