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DISPLACEMENT MECHANISM FORCES IN TUBE BUNDLE

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Abstract: The article deals with experimental determination of fluid coupling forces acting on tubes that are in a cross flow. The real tube bundle is simulated by a System of cylindrical dummies. The method utilizes the possibility of superposition, and on this principle the forces are measured in pairs of dummies. During the tests both the tubes are excited by aerodynamic forces and also by sinus forces of two electrodynamic vibrators. There are 6 unknown values that must be solved: inertia, dumping, elastic aerodynamic and mechanical forces. The appropriate movement equation is complex, and so for filling its coefficients it is enough to measure three times: in flowing gas, in stagnant gas, and in not flowing liquid. During the measurements the deflection amplitude of dummies and frequency must be kept constant. The measured quantities are amplitude of deflections, vibrator current proportional to the force, and the phase between them. Only displacement mechanism forces are taken into account.
Keywords: mechatronical method, aerodynamic damping, aerodynamic stiffness

1 INTRODUCTION

There are two main aerodynamics mechanism causing vibration of tubes in the tube bundles of heat exchangers: aeroelastic mechanism and turbulent buffeting. Buffeting is induced by stochastic fluctuations of velocity and pressure, given by turbulent vortices arising in the flow between tubes in a bundle. Appropriate tube vibrations are also generally stochastic, with varying amplitude and frequency, and therefore weak. But tubes also choose from the spectrum of aerodynamic turbulent forces the part lying in the narrow surrounding of the tube natural frequency. This resonant vibration is more periodic and large, though a little variable in time.

The basis of the aeroelastic mechanism is quite different: if a tube is deflected from its normal position in a bundle, then the flow in its neighbourhood is changed, and there arise another pressure and velocity distribution. As a consequence we obtain a supplementary force that can enhance or, on the contrary, suppress the original deflection of the investigated tube as well as the adjacent tubes. It means that small vibrating deflections are enhanced or lowered. The first case is dangerous because it causes the sinus vibration of large amplitudes that can damage the structure in a short time. We meet such phenomena, for instance, in steam condensers where the tubes are some-times bumping against each other until their destruction.

If we need to discern the aeroelastic mechanism and the buffeting, we can, e.g., utilize the fact that the first vibration is deterministic, while the other stochastic. This demand is not necessary to be fulfilled entirely in the submitted task, as we are interested only in the aeroelastic mechanism, and for this purpose it is enough to eliminate the turbulent forces and the stochastic tube displacements.

2 THE MECHATRONICAL DEVICE

Elimination of the mentioned turbulent force, and therefore buffeting is performed in our experimental rig by adding the opposite stochastic force corning from electrodynamic vibrator and acting on the tested tube. The tube as a part of experimental bundle is a short stiff cylinder located in the measuring room of a wind tunnel. This dummy is fastened in an elastic parallelogram (see Fig. 1 or Fig. 3) enabling vibrational movements. At the one end of the parallelogram cross-beam there is the vibrator, while at the other end the non-contact sensor of deflections is situated.

The sensor represents the inlet member of the mechatronical feedback loop of the vibro-system. Further important members according to Fig. 1 are: the numerical regulator, the sinus signal Generator enabling the change of frequency, amplitude and phase, the data acquisition unit, the personal computer, and at the end the electrodynamic vibrator. The lower described method of measuring demands from the feedback loop either the keeping of the dummy sinusoidal vibration of the prescribed amplitude and frequency, constant during the tests in different environments, or the dummy motionless state, though the cylinder is under attack of various aerodynamic forces including the turbulent ones.

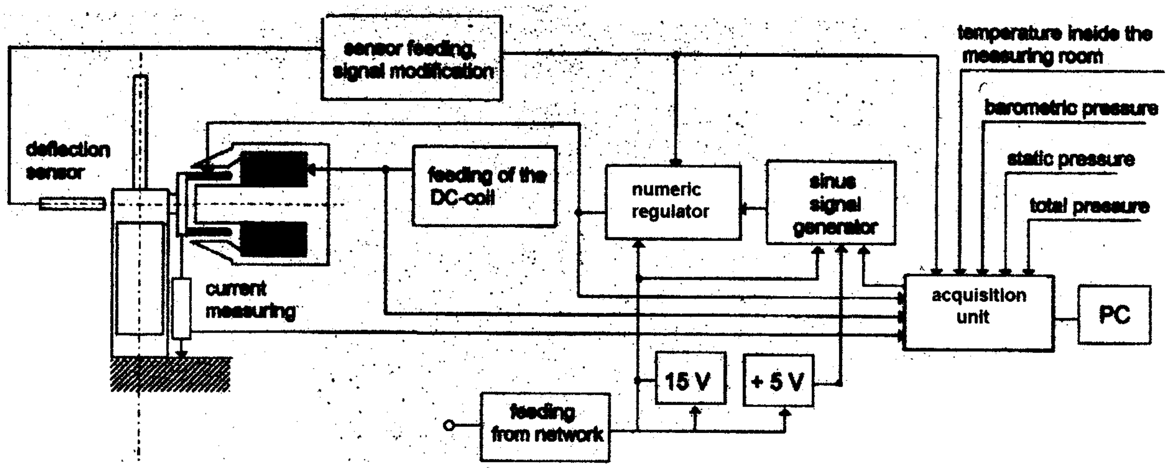

Figure 1. Feedback loop of one dummy

The regulator gets the required sinus or zero deflection signal from the generator, and compares it with the signal from the sensor. The signal deviation represents a regulator departure that is continually eliminated, essentially by turning the phase and by appropriate AC amplifying the vibrator feeding. The regulator is capable of compensating the stochastic deflection fluctuations of the dummy with the rest of about 4% of the original fluctuation value. The result of regulation is the sinus or zero time behaviour of the deflection, yet the stochastic course of the vibrator force. These facts are documented in Fig. 2, where measurements on two neighbour dummies are shown: in the upper half there are the time courses of the forces including their spectra, in the lower part the sinus and zero deflections, again with their spectra. Cleanliness of deflection curves is sufficient for our purpose.

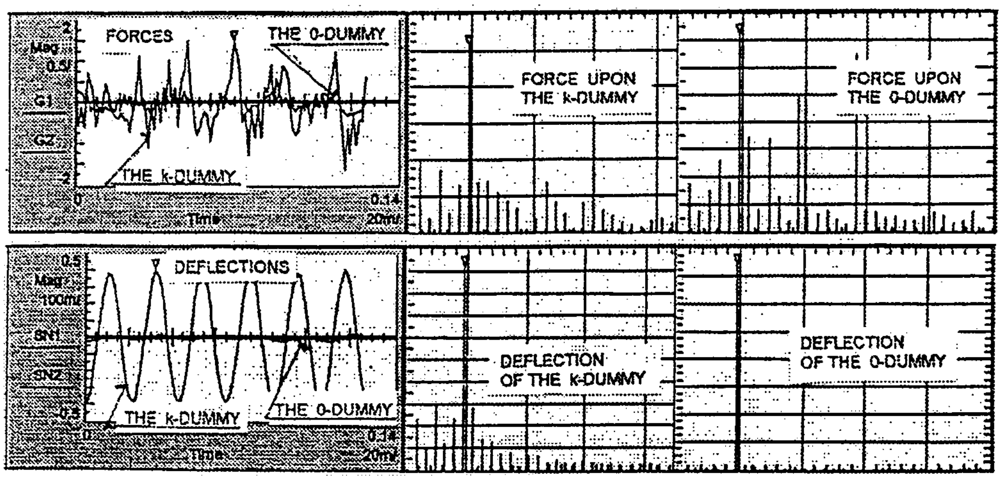

Figure 2. One of the measurement records

The aeroelastic force hidden in the complex stochastic force acting on the motionless dummy must be selected by using the Fourier transformation that is carded out numerically in PC. Besides the just mentioned values, there are some other sampled signals coming from the data acquisition unit to PC: pressure and temperature of flow in the measuring room. A special computer code counts the inlet velocity from them. The first step is the checking up of the amplitude deviation of the dummy from the prescribed value. If the deviation exceeds the tolerance the computer orders the generator to change the amplitude of the sinus excitation. If the deviation is within the tolerance the code measures the force, and the phase angle between the deflection and the force of the tested dummy. The Fourier transformation (FT) is applied to both the signals. After executing the FT, the code selects from the frequency transforming series those samples (i.e. pictures) which belong to the model frequency of the dummy (natural frequency equals to the frequency of the aeroelastic vibration).

3 MOVEMENT EQUATION

Let us assume a cross-flown tube bundle, and in it a tube denoted as the central *0*. The real tube bundle of a heat exchanger in the described method is simulated by a bundle of short, stiff cylinders on elastic supports, this bundle being situated in the measuring room of the wind tunnel. It is impossible to test the influence of all the neighbour dummies on the central one simultaneously. Therefore, this coupling influence is examined consecutively, it means in couples of dummies that are formed by the central cylinder *0* as well as by one of the adjacent cylinder denoted k. Only these two dummies are supported elastically, the others are stiff. This is possible, provided the superposition conditions are fulfilled. Both the elastically supported dummies are equipped with a vibrator and a non-contact sensor of deflection.

Dynamic forces acting on the central dummy 0 in direction *z (z = x or y)*, and occurring at sinusoidal vibrating of k-dummy are: mechanical forces, mechanical coupling forces, aerodynamic coupling forces (=aeroelastic *f.*), turbulent force, and vibrator force. So the movement equation in Z- direction consists of the following terms:

$$m\ddot{z}_0 + b\dot{z}_0 + {}^{M}F_{0k} + {}^{A}F_{0k} + {}^{T}F_0 = F_0 \qquad (1)$$

Out of them the mechanical coupling forces are excluded by a special performance of the frame carrying the two vibrating systems. Also the turbulent force is eliminated by conveying the corresponding anti-force to the stochastically vibrating dummies, as it was described above. If we leave out both these forces, decomposing the aeroelastic ones to the inertial, dumping, and elastic part, then we obtain equation (2). The aeroelastic vibration of the 0-durnrny is caused by the movement of the *0*-tube itself, and that of the neighbour k-tube.

$$\begin{aligned} &m\ddot{z}_0 + b\dot{z}_0 + k\,z_0 + rS\,{}^{A}m_{00}\,\ddot{z}_0 + rDw\,{}^{A}b_{00}\,\dot{z}_0 + \frac{1}{2}rw^2\,{}^{A}k_{00}k\,z_0 \\ &+ rS\,{}^{A}m_{0k}\,\ddot{z}_k + rDw\,{}^{A}b_{0k}\,\dot{z}_k + \frac{1}{2}rw^2\,{}^{A}k_{0k}\,z_k = F_0 \end{aligned} \qquad (2)$$

It is evident that the aeroelastic forces are expressed in the similar way as the mechanical ones, i.e. in dependence upon the tube deflection, and its first two derivatives. Aeroelastic force terms contain velocity of the flow w, gas density **r**, tube diameter *D*, tube cross-section *S*, and the so-called fluid coefficients of inertia, dumping and stiffness that are to be determined as the main goal.

We should explain the lower and the upper indices of the fluid coefficients. For example, ${}^{A}k_{0k}^{yx}$ means aerodynamical stiffness coefficient of the *0*-tube vibrating in y-direction and influenced by *k*-tube in x-direction. On inducing the k-dummy into a periodic sinus movement, the aerodynamically coupled *0*-dummy will vibrate with the same frequency ***w*** , but with a phase delay of ***w**₀*, During this state, the *0*-dummy is exposed to the vibrator force of the same frequency delayed by ***F**₀* behind *Z₀* according to (3).

$$z_k = |z_k|e^{i\nu t}\ ,\ z_0 = |z_0|e^{i(\nu t - j_0)}\ ,\ F_{0k} = |F_{0k}|e^{i(\nu t - f_0)} \qquad (3)$$

Putting (3) into (2) and introducing substitutions (4) in the result, after a small rearrangement, we get the basic equation (5) for evaluating aeroelastie forces, where $j = j_0 - f_0$. The expressions (4) are modules of mechanical and aeroelastic forces. They will be determined at first.

$$\begin{aligned} &|MS_0| = \omega^2 m|z_0|, \qquad |MU_0| = \omega b|z_0|, \qquad |MP_0| = k|z_0| \\ &|AS_{00}| = \omega^2\rho S\,{}^{A}m_{00}|z_0|,\ |AU_{00}| = \rho Dw\omega\,{}^{A}b_{00}|z_0|,\ |AP_{00}| = \frac{1}{2}\rho w^2\,{}^{A}k_{00}|z_0| \\ &|AS_{0k}| = \omega^2\rho S\,{}^{A}m_{0k}|z_k|,\ |AU_{0k}| = \rho Dw\omega\,{}^{A}b_{0k}|z_k|,\ |AP_{0k}| = \frac{1}{2}\rho w^2\,{}^{A}k_{0k}|z_k| \end{aligned} \qquad (4)$$

$$|F_{0k}|e^{i\varphi} + (|MS_0| + |AS_{00}|) - i(|MU_0| + |AU_{00}|) - (|MP_0| + |AP_{00}|) + (|AS_{0k}| - i|AU_{0k}| - |AP_{0k}|)e^{i\varphi_0} = 0 \qquad (5)$$

4 DETERMINATION OF AEROELASTIC FORCES AND COEFFICIENTS

The 6 unknown modules of aeroelastic forces contained in equation (5) require for their determination 6 independent equations. They all can be derived from the basic complex equation (5).

At first, this one is possible to divide it into 2 equations, one valid for the real parts, and the other for the imaginary ones. Then we can apply these equations to 3 fluid states in the tested tube bundle. We have chosen: flowing air, stagnant air, stagnant water. If the frequency and amplitude of the vibrating dummies are held constant, we obtain the required independent equation system. However, it is necessary to check up its solubility, i.e., the non-zero value of the system determinant. Nothing happens, if the 3 mechanical modules are not known, because they get eliminated in the evaluation process. The same is valid for the mechanical coupling forces that were omitted earlier in the movement equation.

The process of the measurement is as follows:

a) In air flow, The air flow is let into the tube dummy bundle. The 0-durnmy is held in the sinus oscillating by its vibrator, the k-dummy is kept motionless. Therefore, the phase angle (P, between the deflections is supposed to be zero, and the movement equation (5) can be reduced to (6). In the next step of our experiment we put the k-dummy into oscillation with the same amplitude, and stop the 0-dummy. So for this case it is possible to rewrite the equation (5) into (7).

b) In stagnant air, We turn off the stream of air and repeat the two above described steps, keeping both the previous deflection amplitude and the frequency. The movement equations (6), (7) change their forms into (8), (9).

c) In stagnant water, We repeat the two measurements as before, but in stagnant fluid of much higher density, again with the same amplitude and frequency of vibrations. The advantage of the high density is the much stronger aeroelastic inertia forces that can be later determined from the respective equations (10),(11).

$$\left|{}^{W}F_{00}\right|e^{i\,{}^{W}\varphi_{00}}+\left|MS_0\right|+\left|AS_{00}\right|-i\left(\left|MU_0\right|+\left|AU_{00}\right|\right)-\left(\left|MP_0\right|+\left|AP_{00}\right|\right)=0 \qquad (6)$$

$$\left|{}^{W}F_{0k}\right|e^{i\,{}^{W}\varphi_{0k}}+\left|AS_{0k}\right|-i\left|AU_{0k}\right|-\left|AP_{0k}\right|=0 \qquad (7)$$

$$\left|{}^{0}F_{00}\right|e^{i\,{}^{0}\varphi_{00}}+\left|MS_0\right|+\left|AS_{00}\right|-i\left|MU_0\right|-\left|MP_0\right|=0 \qquad (8)$$

$$\left|{}^{0}F_{0k}\right|e^{i\,{}^{0}\varphi_{0k}}+\left|AS_{0k}\right|=0 \qquad (9)$$

$$\left|{}^{H}F_{00}\right|e^{i\,{}^{H}\varphi_{00}}+\left|MS_0\right|+\left|HS_{00}\right|-i\left|MU_0\right|-\left|MP_0\right|=0 \qquad (10)$$

$$\left|{}^{H}F_{0k}\right|e^{i\,{}^{H}\varphi_{0k}}+\left|HS_{0k}\right|=0 \qquad (11)$$

After making the following differences of the last equations, we get rid of all the mechanical modules:

(6) - (8) : $$\left|{}^{W}F_{00}\right|e^{i\,{}^{W}\varphi_{00}}-\left|{}^{0}F_{00}\right|e^{i\,{}^{0}\varphi_{00}}-i\left|AU_{00}\right|-\left|AP_{00}\right|=0 \qquad (12)$$

(7) - (9) : $$\left|{}^{W}F_{0k}\right|e^{i\,{}^{W}\varphi_{0k}}-\left|{}^{0}F_{0k}\right|e^{i\,{}^{0}\varphi_{0k}}-i\left|AU_{0k}\right|-\left|AP_{0k}\right|=0 \qquad (13)$$

(8) - (10): $$\left|{}^{0}F_{00}\right|e^{i\,{}^{0}\varphi_{00}}-\left|{}^{H}F_{00}\right|e^{i\,{}^{H}\varphi_{00}}+\left|AS_{00}\right|-\left|HS_{00}\right|=0 \qquad (14)$$

(9) - (11): $$\left|{}^{0}F_{ok}\right|e^{i\,{}^{0}\varphi_{0k}}-\left|{}^{H}F_{0k}\right|e^{i\,{}^{H}\varphi_{0k}}+\left|AS_{0k}\right|-\left|HS_{0k}\right|=0 \qquad (15)$$

We see that the first two equations (12) and (13) have the same structure, and the other ones (14) and (15), too. Consequently, we leave out the lower indices, and divide the simplified equations into the real and the imaginary part. From both the terms it is possible to evaluate the modules of the aerodynamic forces, or their fluid coefficients bound on the length 1 of the dummy in flow. In this way the task is formally solved.

$$\left|{}^{w}F\right|e^{i\,{}^{w}\varphi}-\left|{}^{0}F\right|e^{i\,{}^{0}\varphi}-i\left|AU\right|-\left|AP\right|=0 \qquad (16)$$

$$\left|{}^{0}F\right|e^{i\,{}^{0}\varphi}-\left|{}^{H}F\right|e^{i\,{}^{H}\varphi}+\omega^2\rho S\,{}^{A}m\left|z\right|-\omega^2\rho_H S\,{}^{A}m\left|z\right|=0 \qquad (17)$$

$$\left|AP\right|=\left|{}^{w}F\right|\cos{}^{w}\varphi-\left|{}^{0}F\right|\cos{}^{0}\varphi \quad [N] \quad \longrightarrow \quad {}^{A}k=2\left|AP\right|/\varphi w^2\left|z\right| \quad [-] \qquad (18)$$

$$\left|AU\right|=\left|{}^{w}F\right|\sin{}^{w}\varphi-\left|{}^{0}F\right|\sin{}^{0}\varphi \quad [N] \quad \longrightarrow \quad {}^{A}b=\left|AU\right|/\rho Dw\omega\left|z\right| \quad [-] \qquad (19)$$

$$\left|AS\right|=\omega^2\rho S\,{}^{A}m\left|z\right| \quad [N] \quad \longleftarrow \quad {}^{A}m=\left(\left|{}^{H}F\right|\cos{}^{H}\varphi-\left|{}^{0}F\right|\cos{}^{0}\varphi\right)/\omega^2 S\left|z\right|(\rho-\rho_H)l \quad [-] \qquad (20)$$

5 THE EXPERIMENTAL RIG

The measurement devices located inside the wind tunnel have to fulfill plenty of requirements. Among them it is the ability to excite the dummy to the required amplitude and frequency, and to keep both the values constant for all the pairs of dummies during the measurement in the flowing fluid, not flowing fluid and motionless water. The frequency of oscillating is given by the model similarity theory, the criteria applied being the Strouhal number *Sh = f D/w,* and at high velocities the Mach number *Ma =w/a.* In order to excite easily the vibrations having the model frequency, the basic natural frequency of the whole suspension including the dummy is tuned just to the model one.

Figure 3 shows the dummy vibrating support. The basis of the vibro-system is a parallelogram. The lower part of it is fixed to the frame that is also joined to the electrodynamic vibrator. The web plates of the parallelogram are the planchettes by the length and thickness of which the natural frequency of the system is tuned. To the upper cross-beam of the parallelogram there is fastened a small coil of the vibrator which is fed from the generator. The large pre-magnetic coil is supplied from the stabilized source by the DC. On the other side of the cross-beam there is a non-contact sensor for scanning vibration deflections. The vibrating dummy in the wind tunnel has its own natural frequency, five times higher than is the natural frequency of the whole vibro-system that is the same as the above mentioned model frequency. Consequently, the dummy does not swing during vibration, and makes only parallel movements. The final tuning of the vibro-system is carried out by means of small weights placed upon the end of the dummy under the cross-beam.

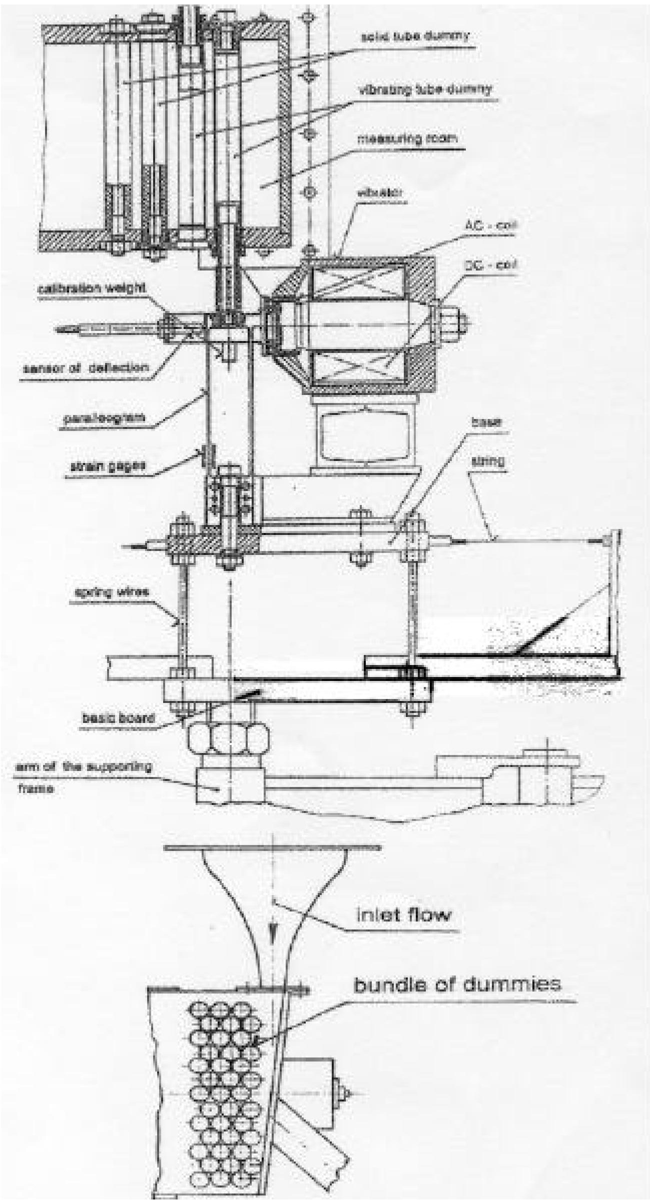

Figure 3. The lower vibro-system

The working part of tube dummy is placed in the measuring room of the wind tunnel together with the other cylinders of the bundle. There is another elastically bung dummy with identically tuned vibro-system. The other dummies are rigid. For the reason of accessibility, there is one vibrating dummy (*0*) hung under the measuring room, the other one (*k*) is placed above. But for the measurement in water both the dummies are to be hung, of course, above the vessel. The core of the vibro-system is fixed to the basic board by 3 spring wires. By them, the basic natural frequency of the whole vibro-system is tuned to 1/50 of the model one, and there is a tendency to a slow pendulum motion. This inadmissible phenomenon is excluded by 4 thin strings connecting the base plate with the basic board. All these low tuned elastic elements help to prevent the transfer of energy from the vibrating dummy to the frame, or to the other vibro-system. The basic board is pivoted, hence it is possible to change the direction of vibrating to the axis x or y. The same is enabled by the second vibro-system, so that there are 4 variants of attachments - the force upon *0*-dummy versus deflection of the k-one is *x-x, x-y, y-x* and *y-y*.

One kind of the fluid coefficients is indeterminable by using the described 1*D* supporting parallelograms, namely those coefficients, which represent influence of the body deflections on the cross aerodynamic force acting on the same body in the presence of the others $m_{00}^{xy}, m_{00}^{yx}, b_{00}^{xy}, b_{00}^{yx}, k_{00}^{xy}, k_{00}^{yx}$ For these 6 coefficients special elastic supporting system was prepared with two degrees of freedom. There was inserted a further but small parallelogram between the present one and the tube dummy, depicted in Fig. 4, being orientated perpendicularly to the main parallelogram. That small one is equipped with strain gages and serves for measuring the force as a strain gage scale, while the large one is used for the deflection measurement as before. The natural frequency of the system was not changed.

6 SOME RESULTS

In the lower part of Fig. 3 we can see the studied tube dummy bundle. As in the modelled steam condenser, the inlet air flow is tangential to the first row of tubes, and then n is forced to turn by 90° into the depth of the bundle. The tube grid is triangular with a relative pitch *t/D*=1.4, where the diameter *D*=20 mm and the active tube length in flow *l*=150 mm. The natural frequency of the whole dummy including its support is 47 Hz. The dummy deflection amplitude was kept at 0.4 mm, still belonging to the linear region of the dependence deflection versus force. The vibrometer signals were sampled 16 times/period during 256 periods, which means that the time of one sampling was 5.12 seconds. This process was repeated 3 times, and from the results there were taken average values. At every velocity 2 or 3 such values were measured in order to exclude random influences. The representative velocity is the mean one related to the narrowest gap among the tubes. The inlet velocity in front of the tube bundle is three times higher. The fluid coefficients as a function of the gap velocity represent the result of the measurements. In the appropriate 6iagrams the scattered points are replaced with one or two power series functions up to the fourth degree.

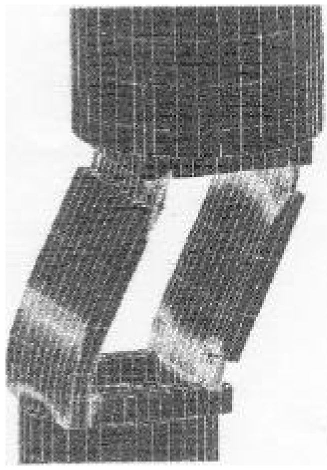

Figure 4. Strain gage scale

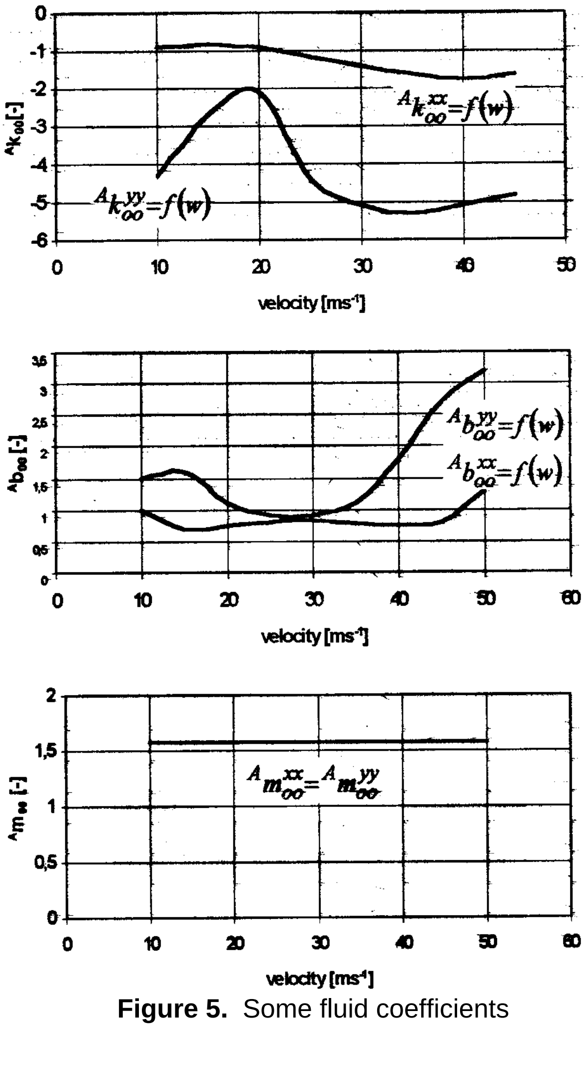

Figure 5. Some fluid coefficients

Until now, the measurements have been made on the cell formed by one central dummy in the third row and by 8 surrounding ones. Out of the number of 108 obtained fluid coefficient curves we chose those 6 in Fig. 5. They contain the most important fluid coefficients of the central dummy that express the influence of its vibration deflections on the aeroelastic forces acting on it itself in the same directions, as a function of the gap velocity. We have not found comparable data of other investigators, so we tried to check up ours by numerical way – namely the added masses in stagnant water on the basis of the potential flow theory according to [1], and the air stiffness coefficients by quasidynamic computer simulation. The difference of measured and computed fluid mass coefficients was acceptable, about 6 %. Worse results were obtained in the case of the fluid stiffness coefficients. The reasons are probably given by the inaccurately solved flow in the tube bundle by the computer code Fluent, and by the method of the evaluation based on a not-precise determination of derivatives of the force by deflection.

The error analysis showed that the scatter of the points is due to temperature influences. They cause the false measurements of angle phases between the dummy displacements and the aerodynamic forces as a consequence of the parallelogram dilatation. This can be avoided by keeping a constant temperature, or by changing the parallelogram material. Instead of Aluminium (dural) there should be used invar, as a very low-expansion alloy. Further dilatations occur in the tube bundle, where the shifts among the stiff cylinders, fixed to the tunnel, and the dummies, suspended independently of the tunnel, arise. It is necessary to elastically detach the measuring room from the rest of the wind tunnel. The mentioned arrangements are executed at present time. As for the removing turbulent forces by the numerical regulator - this problem is much better solved now than it was two years ago, but still there remain about 3-5 % of perturbations out of the 100 % that would occur without any regulator. The nowadays technological possibilities do not provide a better regulator, and we do not think that this may be a remarkable resource of mistakes.

7 CONCLUSION

The described mechatronical method works, and can give correct as well as sufficiently accurate results after some technical improvements of the experimental rig that are now being prepared. The project is supported by the Grant Agency of the Czech Republic.

REFERENCES

[l] S.S. Chen, *Flow-induced vibration of circular cylindrical structures.* Springer-Verlag 1987
[2] V.A. Tsimbalyuk, Method of measuring transient aerodynamic forces and moments on a vibrating cascade, *Strength of Materials* 28 (2) (1996)
[3] J. Linhart, Z. Hejda, M. Schuster, Experimental determination of fluid coupling forces in a tube bundle, in: Inst. of Thermomechanics AS of the Czech republic, *Proceeding of the 3rd Intern. Conf. "Engineering Aero-Hydroelasticity"'* Prague, September 1999, p. 262 - 267.

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