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ANNULAR-SYNTHETIC-JET ACTUATOR FOR LARGE ACTIVE DISTANCES

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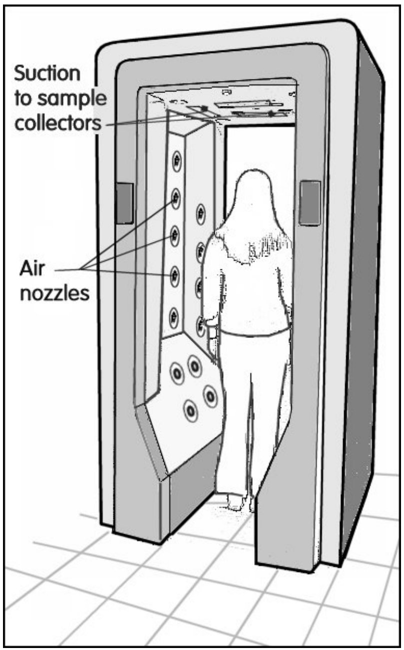
Summary: *Authors investigated aerodynamics of an actuator designed to generate annular synthetic jets reaching to very large distances. It is to be used for detecting illegal substances – and thus identifying terrorists and criminals.*

1. Introduction

Terrorism became one of the fundamental problems at the beginning of 21st century. The critical factor behind its success is economy favouring the terrorists (e.g., Jain and Mukand, 2004). It is much cheaper to perform a terrorist attack than to prevent it. The crude explosive devices terrorists use are inexpensive while maintaining safety requires deploying, maintaining, and manning costly systems and organisations. Essential is early warning which, to be an efficient deterrent, calls for large numbers of detectors deployed at many locations. The most



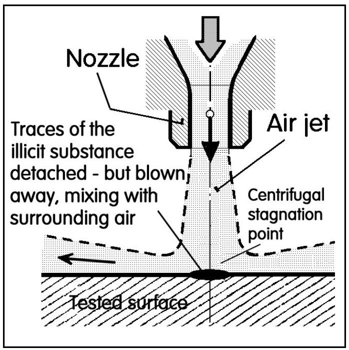


Figure 1 (Left) A typical present-day portal detector with air-jet actuators unit for releasing traces of dangerous and illegal substances from clothes of persons passing through them.

Figure 2 (Right) The air jets used in present detectors mix the critically small amounts of detectable traces uncontrollably with surrounding atmospheric air.

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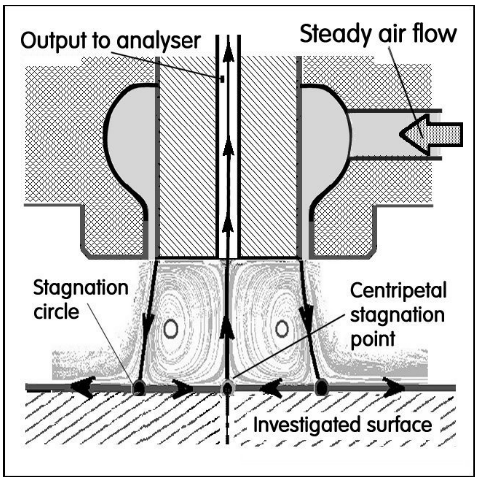
effective preventive measure is detecting traces of explosives and other dangerous substances left on clothes of those people who recently handled them. This detection is currently mostly done by trained dogs. These are almost always in short supply, and their long-term training and the need for dedicated supervisor persons are very expensive.

A solution is sought in use of detectors (Tesař, 2007), most conveniently used arranged into portal units (Fig. 1) through which persons have to pass one by one (Settles, 2006). Their operation actually, to a certain degree, mimics the detection by dogs. To release the detected substances from the surface on which they are immobilised, dog use jets of exhaled from lungs alternating with inhaling by which the substances are moved towards the olfactory sensing organs. The problem is the required extreme sensitivity of the analyser. In the current portal units this problem is aggravated by the acting air jets (Fig. 2) dispersing the already very small traces into the surrounding air. The collectors taking the sample into the analyzer are usually positioned in the top part of the portal (using the thermal air convection currents produced by the person). Obviously, the traces reaching the collectors are very much diluted.



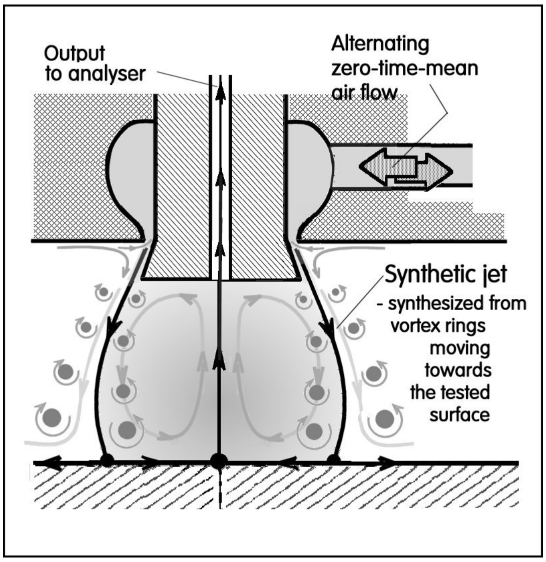


Figure 3 (Left) An annular jet can surround the space between the collector leading to the analyser and the source of the detected substances - so that the latter are prevented from moving away into the atmosphere. However, the large amounts of supplied air still mix with the small amounts of the substances and this places extreme requirements on analyser sensitivity.

Figure 4 (Right) The proposed alternative: synthetic annular jet with zero time-mean supplied air flow. The pulsatile character also helps in releasing the detected traces from the surface.

The dilution is decreased, according to Fig. 3, if the nozzle generating the air jet is annular and is combined with the collector, which it surrounds. The generated annular jet provides a protection. It surrounds the space between the interrogated area on the surface and the collector leading to the analyser, and thus prevents an uncontrollable mixing of the sample with the atmospheric air. Nevertheless, the annular jet is also formed by bringing in a relatively large amount of additional air (supplied from a compressor) and the sample is inevitable mixed with some of this air. A solution is proposed (Tesař and Trávníček, 2006) in using the annular synthetic jet, according to Fig. 4. This is formed by means of the aerodynamic rectification phenomenon (Tesař 1982, 2008), which was investigated by the present principal author for uses in fluidic systems (Tesař 1976, 1980, 1981a, 1981b, 1982, 1984, 1991, 1996) before it received its present name by prof. Glezer (e.g., Smith and Glezer, 1998).

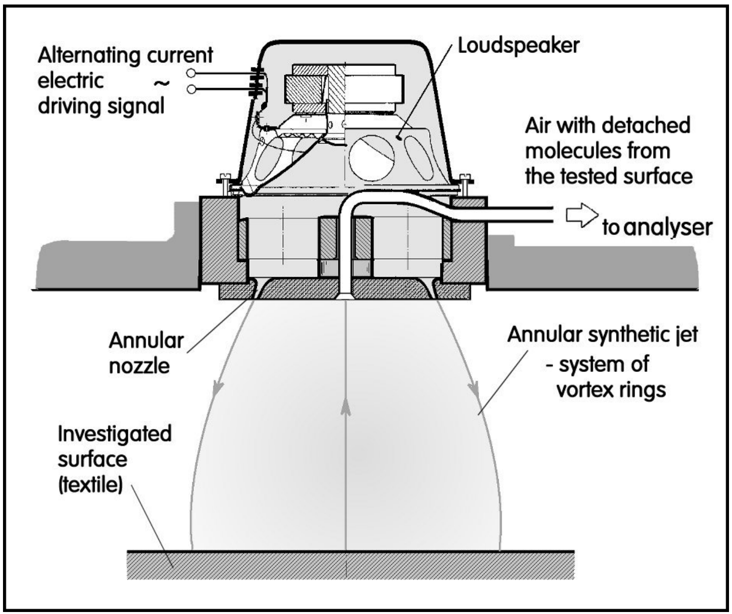


Figure 5 The basic idea of the detector sensor combined with an actuator generating an annular synthetic jet (Tesař and Trávníček, 2006).

2. Investigated laboratory model

For verification of the idea, a model of the detector combined with the synthetic-jet actuator based on the idea presented in Fig. 5 was built as shown in section view in Fig. 6. The alternating flow for the jet generation was produced by standard woofer loudspeaker ARN-165-01/4 of rated short-term maximum power 300 W supplied by harmonic driving signal. The basic question to be answered by the tests is how large action distance between the annular nozzle exit and the investigated surface (the textile on the person) may be achieved. This is due to unpredictable size of the persons and its position inside the portal. According to preliminary studies, a distance of 120 mm is considered necessary.

The problem with the recirculation regions formed by annular nozzles, both for steady (Fig. 2) and synthetic (Fig. 3) jets, is they tend to be decreased by the entrainment. The generated annular jet removes the air from the internal protected space and carries it away. This leads to convergence of the outer boundaries of the region.

Dimensions of the cavities of the test model are presented in Fig.7. To make the active distance large, the outer diameter of the annular nozzle of the designed laboratory model was chosen large – its nominal diameter is 130 mm. For the same reason, the shape of the nozzle exit was made rather complicated, defined by two conical surfaces diverting the nozzle flow outwards. To counter the convergence of the time-mean pathlines of the issuing flow, the significant radial outward diverging orientation of the exit velocity vector makes the recirculating region wider: the apex half-angles of the inner and outer cones are 20° and 15°, respectively. Moreover, also to direct the issuing jet more into the outward direction, the nozzle orifice was designed with the 4.15 mm stagger of the exit lips (the internal core is longer than the outer frame). The (nominal) width of the nozzle slot is $b = 1$ mm. The inner diameter of the exit is defined by the exchangeable centrebody plate, which also contains the 9 collector orifices through which the suction is to be applied to remove the sample and send it into the analyser. In the present investigations these orifices were closed off and the centrebody plate was not changed. Earlier experience with pulsating flow through orifices (Tesař, 1989) have shown that the efficiency of generating the alternating output flow may be significantly decreased by the capacitance (Tesař, 2007) of the cavities upstream from the exit. Instead of forming the jet, the pulsating supply tends just to compress and expand the air inside the cavities. To suppress this effect, the volume inside the conical membrane of the loudspeaker was decreased by the inserted solid centrebody.

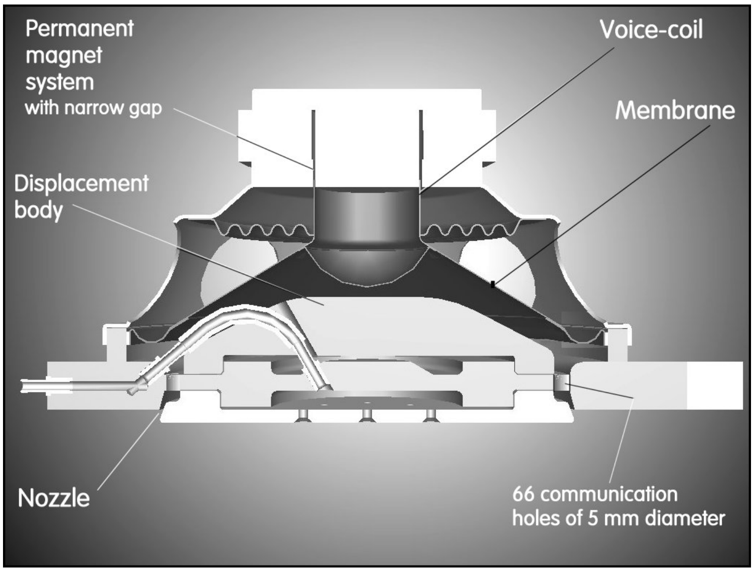
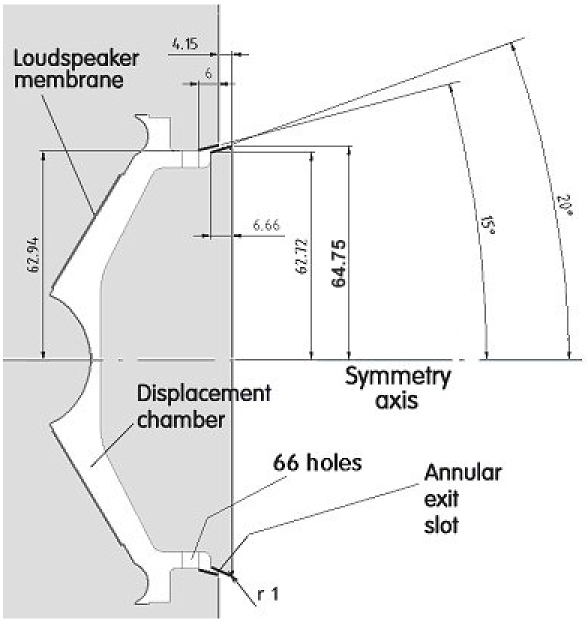


Figure 6 The actuator model – shown in meridian section - used by the authors in their experiment. The key component is a standard loudspeaker ARN-165-01/4 .

3. Experiments

The measurements performed by the authors concentrated on air flow velocity in the generated synthetic jet. The used instrumentation was hot-wire anemometer system CTA 54T30 (DANTEC Dynamics) with standard single-wire probe type 55P16. The probe was traversed in the radial direction by an automatic traversing gear, driven by a stepping motor. At each location the probe remained stationary for the duration of the data acquisition. The computer control of the traversing, as well as an elegant method of data acquisition using the data storage properties of the digital oscilloscope RIGOL DC 1042CD, were devised by Mr. M. Pavelka. Before the actual experiment, the anemometric system was calibrated by comparison with Pitot probe positioned into the same location in the potential core of an auxiliary air jet. The parameters of the adjustment – in particular the probe currents – were used as supplied by the probe and anemometer manufacturer. Since the measured velocities in the actual experiment were in most of the jet flowfield very low, the calibration procedure was set up so as to concentrate on the low-velocity end of the range. The calibration diagram and the quadratic law by which it was fitted are presented in Fig. 9. It should be noted that because of the probe being of the single-wire type, it was sensitive not only to the axial component of the air flow velocity, but also to the radial component – since the heated wire was held oriented with its axis in the tangential direction relative to the nozzle axis. This is why – given the negligible



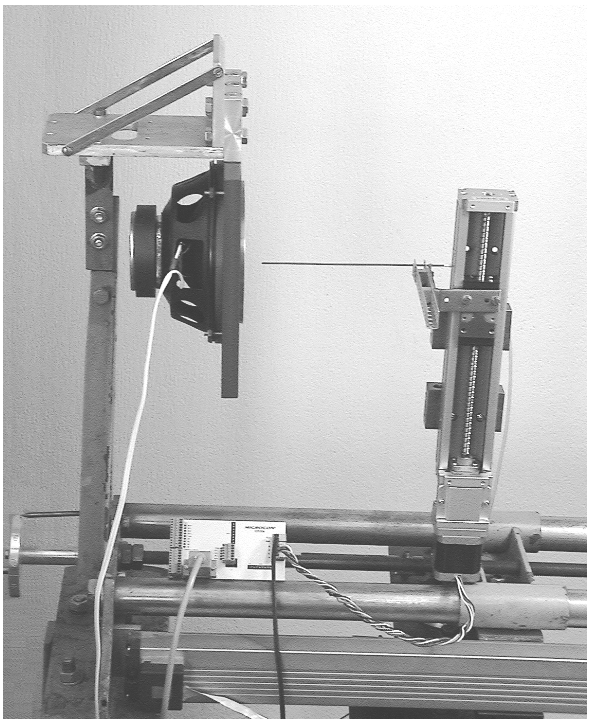


Figure 7 (Left) geometry and dimensioning of the cavities of the actuator model.

Figure 8 (Right) The actuator model with the hot-wire probe traverser during the laboratory tests.

tangential velocity component – the measured value is here described as velocity magnitude. Also, as usual with hot-wire probes, it was impossible to discriminate between positive and negative direction of the velocity.

Actual program of experiments was rather extensive. In the present conference contribution, the discussion will be limited to the results of two experimental series, in both of which the evaluated quantity was the time-mean velocity magnitude, computed as the mean value of the velocity magnitudes acquired (and stored in the oscilloscope) at a particular location of the probe in the flowfield.

4. Size of the recirculation region

In this first test series, the measurements were made in each location of the matrix of 20 x 14 measuring points separated by 5 mm steps: the upper 20 x 5 points of this matrix are visible in Fig. 10, which also shows typical character of the oscilloscope traces as they were observed in two locations near to the nozzle exit. The matrix points in this experiment nearest to the nozzle exit were at the 8.4 mm streamwise axial distance. This separation from the actuator components was chosen for avoiding any possibility of probe collision with them.

Over most of the matrix points, the measured time-mean velocity magnitudes were very small, indeed negligible. Thus of interest were only those locations near to the path of the annular jet issuing from the nozzle slit, as they are seen in Fig. 11. In this diagram, it was possible to identify, by interpolating between the matrix points at the same axial distance from the nozzle, the position of the velocity maxima. These are marked by the black data points in Fig. 11, where these points are connected by the continuous dark line. These points define the extent of the recirculation bubble.

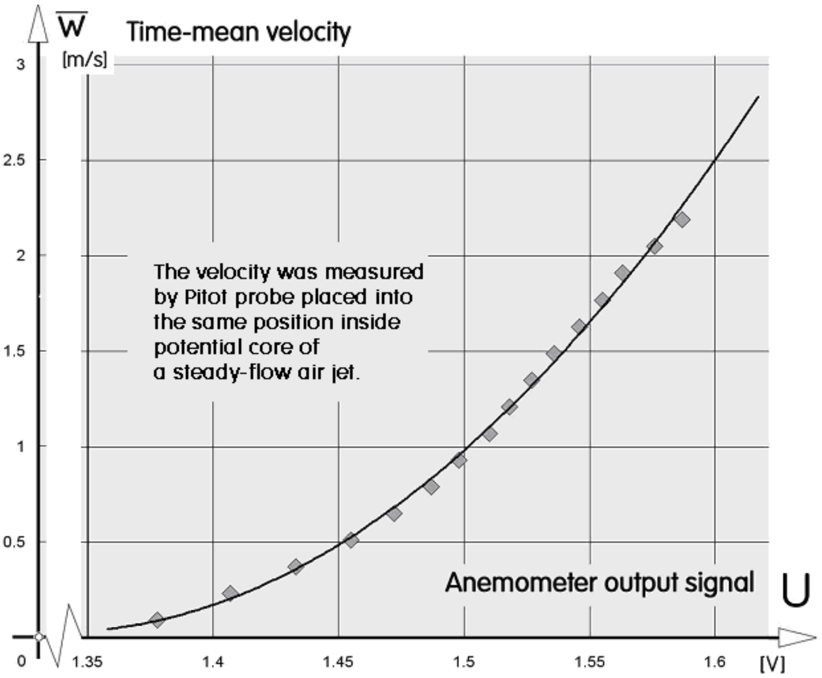


Figure 9 Calibration curve of the hot-wire probe as used in the tests. The calibration procedure was specially set up so as to reach the range of very low velocities.

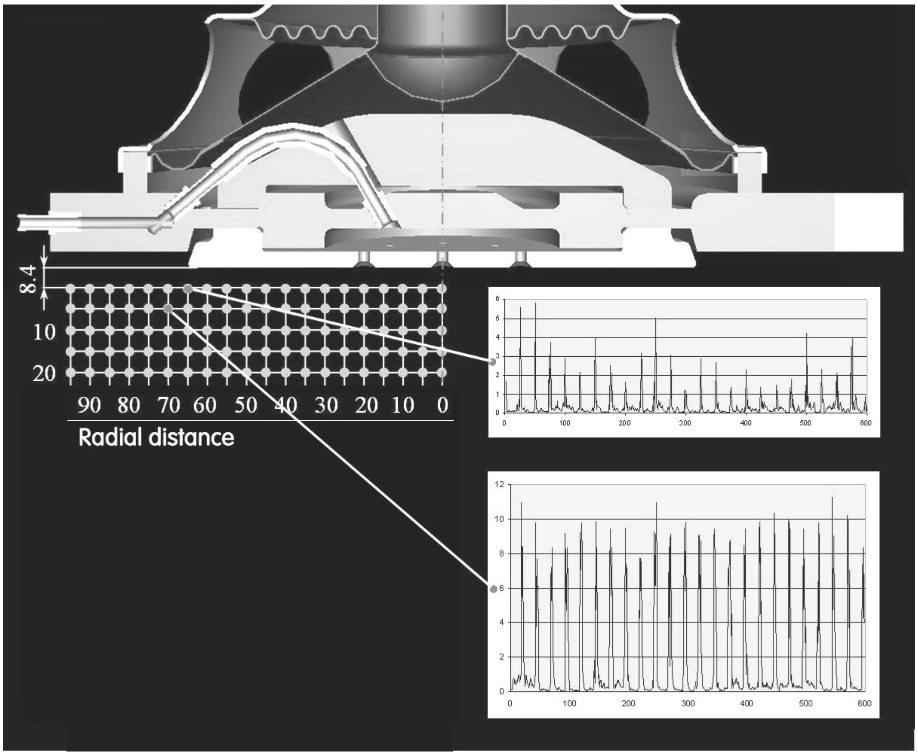


Figure 10 Typical character of the oscilloscope traces obtained by the measurements near the nozzle exit.

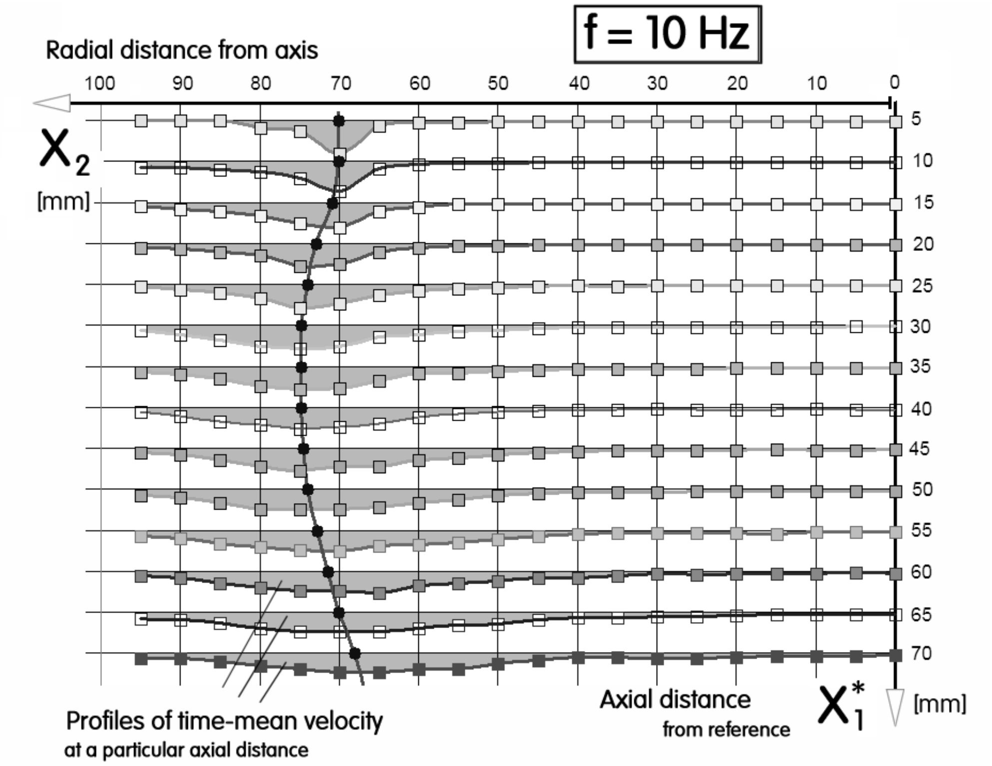


Figure 11 Velocity measurements in the 5 mm x 5 mm step matrix of location points downstream from the actuator nozzle identified the positions of velocity maxima in individual streamwise profiles.

Of course, as the jet width increases in the downstream direction due to the entrainment of the outer air, the precision of determining the maxima decreases. The velocity profiles became very flat and wide. Nevertheless, the maxima could be determined and in Fig. 12, only these maximum points defining the outer boundary of the recirculation bubble are shown. Even though it was not possible to perform the measurements at larger distances from the nozzle, it is obvious that the measured recirculation bubble is quite large – it extends as far as to ~120 mm downstream from the nozzle exit. This value agrees comfortably with the requirement of the active distance for the proposed anti-terrorist application in the detection portals. Thus these measurements document the applicability of the actuator for this particular use. It should be noted that the experiment was performed with driving frequency f = 10 Hz, well below the audible range, which is a significant factor for the applicability – and audible noisy device is not likely to be accepted by the general public.

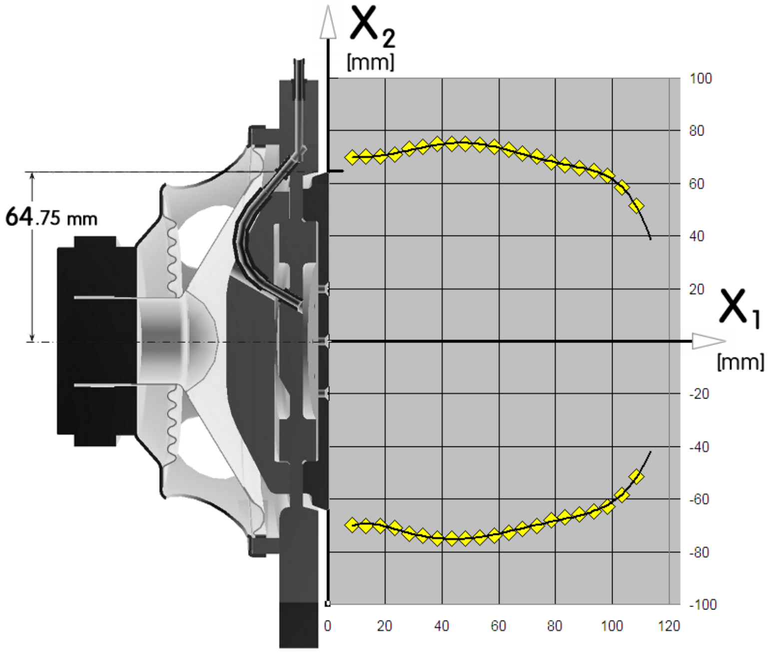


Figure 12 (Right) The extent of the separation bubble identified from the velocity measurements as shown in Fig. 11. The annular synthetic jet was demonstrated to reach to a streamwise distance roughly comparable to the diameter of the nozzle slit.

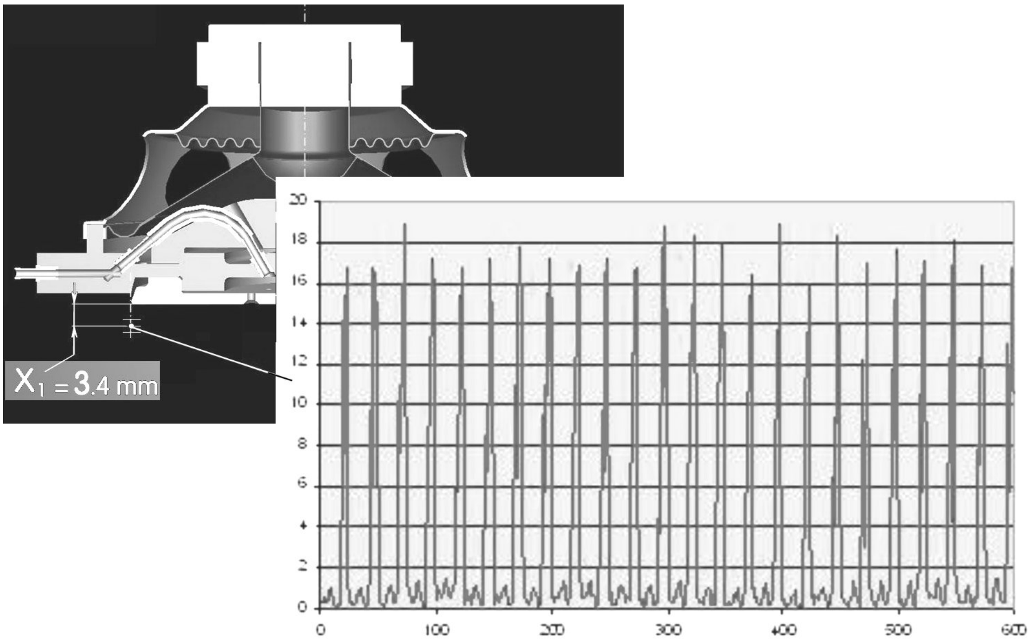


Figure 13 Characteristic oscilloscope signal trace with the small secondary peak between the large velocity pulses, found in the locations immediately downstream from the nozzle generating the annular synthetic jet.

5. Details of velocity profiles and the effect of frequency

This second series of experiments concentrated on the conditions very near to the nozzle. The region in which the velocity magnitude measurements were made is presented in Fig. 14. Safe course of the experiments with the hot wire probe traversed near to the actuator component overcame the initial fears and the hot wire was now positioned as near as 2.4 mm streamwise from inner the core lip (extended from the outer frame). The transverse steps at which the probe was moved were decreased to 1 mm. The profiles were measured at driving frequencies gradually increased in 5 Hz steps from 5 Hz minimum to 65 Hz maximum value.

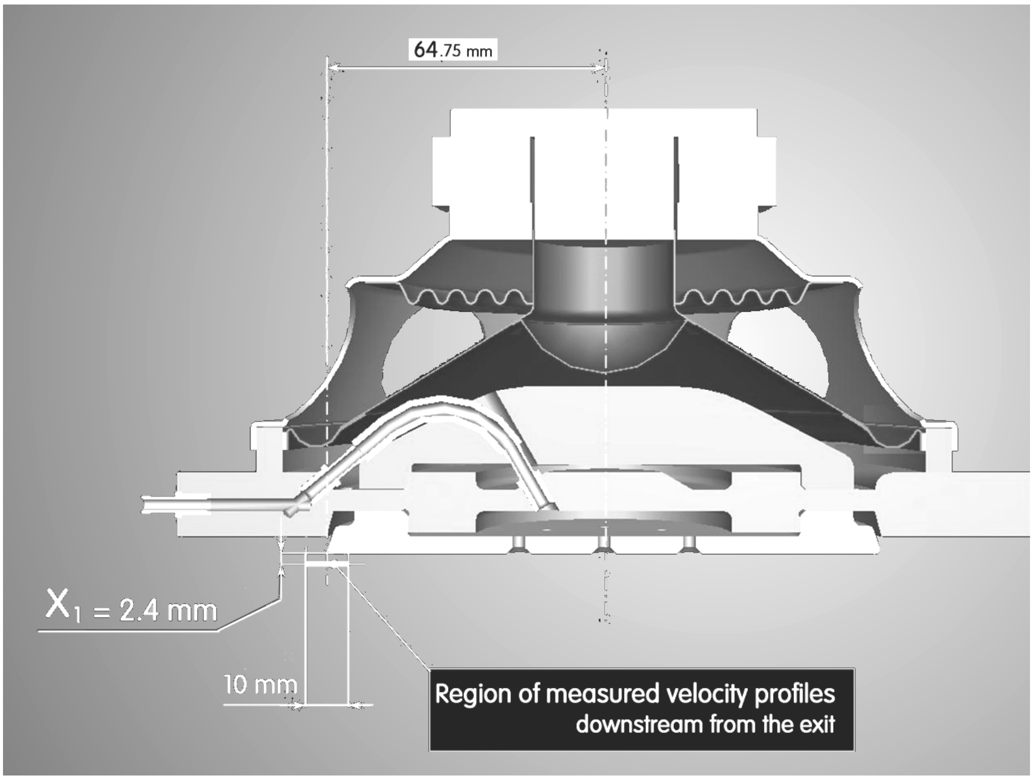


Figure 14 Location of the region immediately downstream from the nozzle. The velocity profiles with the small, 1mm transverse step across the 10 mm wide range were investigated to reveal the influence of the excitation frequency.

Typical examples of the velocity profiles obtained in this measurement series are presented in Fig. 15. They all exhibit a steep maximum roughly in the middle of the traversing range. Immediately apparent is the continuous increase of the velocity with the increasing driving frequency. Also apparent fact is the asymmetry: the velocities away from the maximum are visibly higher on the outer side (i.e. at radii larger than the radius of the nozzle slit measured from the jet axis). At first sight this asymmetry is somewhat strange. The diameter of the nozzle slit is so much larger than the nominal 1 mm slit width that an effect of radial divergence might be expected to be negligible. The explanation of this asymmetry effect we have at this moment is the omnidirectional sensitivity of the hot-wire probe (in the meridian plane) in association with the entrainment flow from outside. The higher velocities the probe found on the outer side are due to the inflow of the outer air from the atmosphere. No doubt another factor that may be responsible is also the already mentioned 4.15 mm stagger of the exit lips: the velocities on the inner side (at smaller radii) are measured at a smaller distance from the wall.

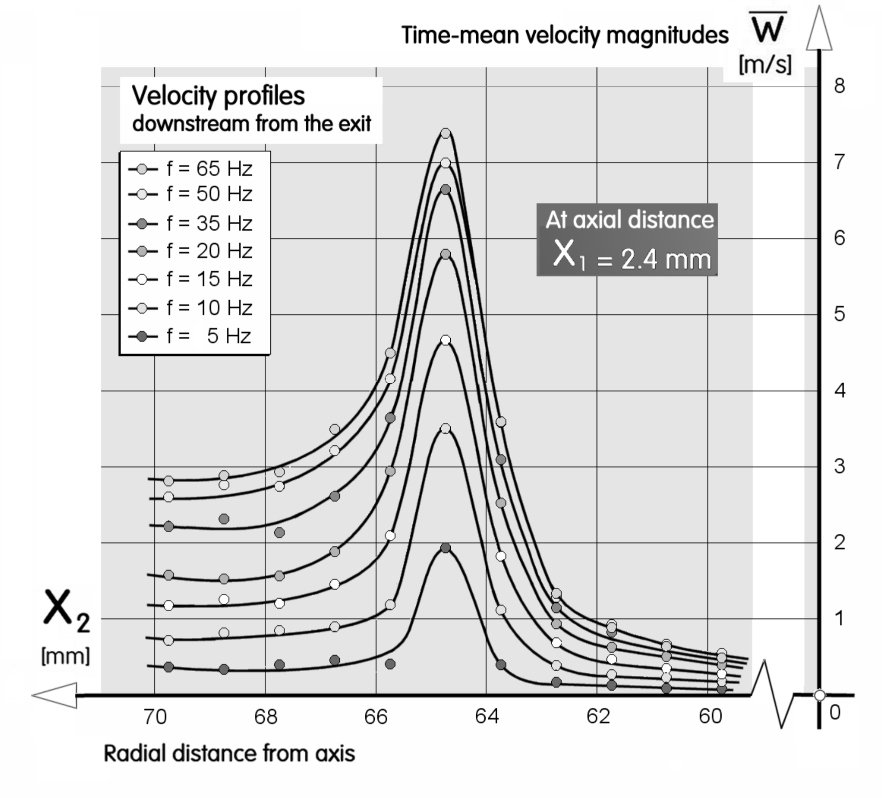


Figure 15 The velocity magnitude profiles obtained by the measurements near the nozzle exit according to Fig. 14.

Another presentation of essemntially the same data is in Fig. 16. In this diagram, the velocity magnitudes at selected radial positions are plotted as a function of the driving frequency. All data pints presented there indicate a continuous growth of the velocity with increasing frequency. Initial slope of the growth is significantly larger. It slows at the frequency about ~25 Hz, but remains positive. Obviously, the 10 Hz driving applied in the experiments the result of which is shown in Fig. 11 is way below of what could be generated with the same actuator. Of course, the associated increase of the audible noise may make this simple way towards a higher effectiveness not acceptable from the practical point of view.

The response to the varied frequency of the investigated actuator was already investigated earlir – in particular it was the subject of the paper by Krejčí et al., 2007. These results were also presented in Tesař, Vogel, and Trávníček (2008). Rather surprisingly, the two sets investigation results disagree. In these previous experiments, the frequency dependence exhibited a clear maximum near to f = 40 Hz – evaluated not only in a series of experiments but also predicted theoretically by Dr. Trávníček. The explanation of this enigmatic fact is to be our next task in foreseeable future. One of the key factors to be considered is the circumstance of the frequency dependence measured by by Krejčí et al., 2007, by means of a Pitot probe (of 0.8 mm i.d., positioned at a location 2 mm downstream from the annular nozzle exit). Another circumstance to be considered is the fact that in the Krejčí et al.

measurements the electric driving power was closely watched and adjusted – in the present case, this was not done and the actual driving power could be influenced by the frequency characteristic of the driving source.

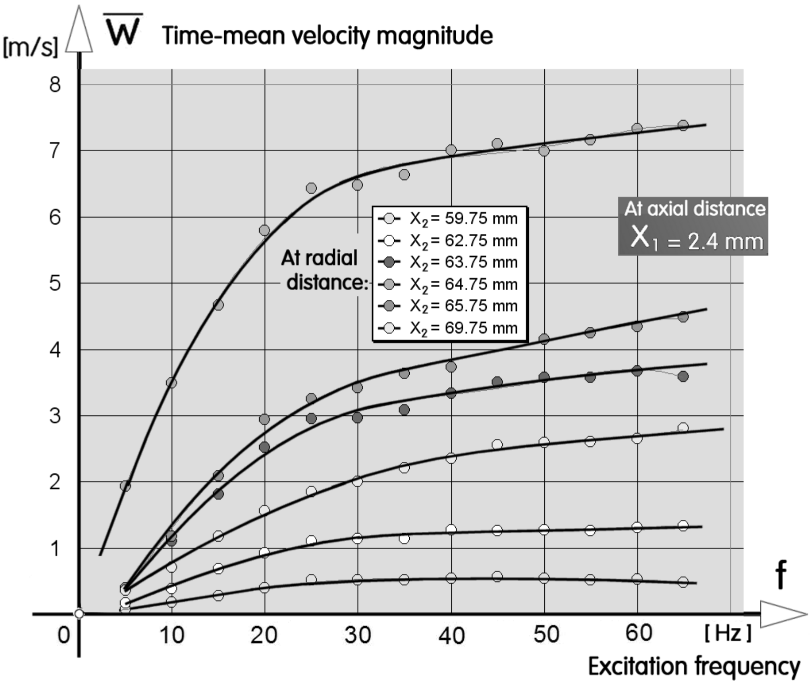


Figure 15 The monotonous growths of the time-mean velocity with increasing excitation frequency in the profiles from Fig. 14.

6. Conclusions

The main reason for the present measurements was accumulating data to be used in the concurrent numerical flowfield computations performed by doc. J. Vogel (see Tesař, Vogel, and Trávníček, 2008). This was done with complete success. Apart from the time-mean velocity distributions, reported in the present paper, we have also accumulated data on the spatial distributions of energy of fluctuation, evaluated by the same approach as described in Tesař and Kordík 2009. The data demonstrate applicability of the concept, but revealed also an enigmatic frequency dependence that has to be a subject of further investigations.

7. Acknowledgement

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