PRELIMINARY RESULTS OF FLOW FLUCTUATION MEASUREMENTS IN THE CRYOGENIC TRANSONIC WIND TUNNEL

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The detailed information about flow fluctuations structure inside the test section of Pilot of European Transonic Windtunnel (PETW) obtained by means of hot-wire anemometer and fluctuation diagram (FD) method within broad and narrow frequency band is presented. Fluctuation diagrams were derived from an array of hot wire output data measured at different overheating ratio of the probe (not less than 8) at freestream Mach numbers \( M = 0.2, 0.4, 0.6, 0.7, \) and \( 0.8 \), total temperature \( T_0 = 118 \ldots 294.7 \) K and unit Reynolds numbers \( Re_1 = (5.54 \ldots 108.6) \cdot 10^6 \) 1/m, respectively. Time series of these output signal data were used to obtain information of statistical and correlation features, mode, and spectral composition of flow fluctuations.

1 INTRODUCTION

The major fluctuations in ventilated test section of most transonic wind tunnels (WTs) have acoustic nature with perforation or slots on the walls as their sources. In cryogenic WTs, the systems of liquid nitrogen injection could be also regarded as potential sources of temperature and velocity flow disturbances. Cryogenic WTs have been exploited more than thirty years, but nevertheless, the fluctuation situation in their test sections is still not documented in quite adequate manner. In order to make the correct assessment of influence of fluctuations on different flow phenomena under study, it is necessary to have the information about the intensity of all three fluctuation modes (vorticity, acoustics, and entropy) as well as their spectral composition by mean of any known
method. The hot wire technique has an advantage because it is sensitive to all three fluctuation types.

Kovácsnay [1, 2] developed the application of hot-wire measurement techniques and proposed the FD to investigate fluctuations in supersonic flow. Spangenberg [3] showed that typical hot-wire sensitivities were a function of both Mach and Knudsen numbers. Morkovin [4] extended the Kovácsnay’s techniques, but the application for high-subsonic compressible flow and transonic flow remained in question. Horstman and Rose [5] and Rose and McDaid [6] applied the supersonic flow hot-wire techniques to transonic flow with the assumption that the hot-wire sensitivities for velocity and for density changes were equal. Stainback et al. [7] have shown that the velocity and density sensitivities for hot-wires could be not equal. A three-wire technique of Stainback et al. was developed to separate the effects of velocity, density, and temperature changes but has not yet received universal acceptance. Further, the authors of this paper have developed the hot-wire application to measure fluctuations of high-subsonic compressible flow and transonic flows. Regarding the fluctuation measurements in cryogenic WTs, there are very limited number of references in the literature [8–13], most of which were performed by using hot-films probes at single overheating ratios.

Therefore, the aim of this paper was to develop, approve, and test the hot-wire technique and fluctuation diagram for studying fluctuation structure in cryogenic transonic flows.

2 EXPERIMENTAL BACKGROUND

2.1 Facility and Running Conditions

At the first stage of studying, the measurements were carried out in PETW, Cologne, Germany, with slotted top and bottom and solid side test section walls. The porosity is 3.4% for the test section or 6.25% per slotted wall. The PETW is a scaled-down (1:8.8) version of cryogenic European Transonic Windtunnel (ETW) with, however, external thermal protection (see details in [11]). It is supposed also to extend the flow fluctuation measurements activity in ETW in the future. The PETW is a facility of closed type with the rectangular test section and dimensions of 0.273 m wide, 0.227 m high and about 1 m long.

Liquid nitrogen is injected into the PETW circuit upstream the compressor for cooling the wind tunnel and achieving of total evaporation of droplets and temperature uniformity. Flow quality in the test section was measured at free stream Mach numbers $M = 0.2, 0.4, 0.6, 0.7, \text{ and } 0.8$ and total temperature $T_0 = 118 \ldots 293 \text{ K}$ which corresponded to the unit Reynolds numbers range $Re_1 = (6 \ldots 109) \cdot 10^6 \text{ m}^{-1}$. Hot wire probes were mounted in the test section at
25 mm from the bottom wall and about 120 mm upstream the slotted area (Fig. 1). This position of the probes was assigned in order to learn the level and spectral structure fluctuations of the flow incoming to the test section after its passing over the PETW circuit.

2.2 Experimental Instrumentation and Technique

Constant current anemometer CCA-6 designed and made at the Khristianovich Institute of Theoretical and Applied Mechanics and hot-wire probes with tungsten sensitive elements 6 and 10 µm in diameter and 1.2 mm in length have been used. Front view of CCA-6 and its description in detail can be found in [14]. The typical measuring system on the base of the CCA-6 is given in Fig. 2.

The personal computer, the external 14-bit analog-to-digital converter E14-440 (ADC), the CCA-6 device, and interconnect cables with adapters are necessary to realize a measuring procedure. Mean and fluctuation signals from a
hot-wire anemometer output are digitized by using two external ADC. Control of the anemometer and communications with the personal computer is realized through the COM port RS-232 of the CCA-6 and USB-COM adapter under the standard interface protocol with switching speed 9600 Kbit/s. The hot-wire anemometer has the built-in microcontroller ADuC-842 with integrated 12-bit ADC and DAC to perform the measuring of all internal parameters of the CCA-6 (current, voltage, etc.).

Interconnection of the hot-wire probe directly with device CCA-6 is provided by means of special four-wire scheme. Such manner of connection layout enables to use hot-wire anemometer at quite long distance from the facility and take into account the change of the connecting cable resistance at the presence of heavy temperature gradients automatically that spares from the routine of fulfillment of the cable compensation procedure. The frequency range of CCA-6 is provided up to 200 kHz at all overheating parameters. However, it was usually used low-pass filter with the cutoff frequency 25 or 50 kHz. Data acquisition from CCA-6 outputs was carried out with the sampling rate 60 and 120 kHz and sample size 128 kB that corresponds to the total sampling time 1 or 2 s. After converting the analog signal to digital type, the data were fed into the PC for further processing.

It is well known that in general case, there can be present one of three different types of fluctuations (modes) or their superposition in compressible flows: vorticity, entropy, and acoustics. In order to separate these, modes one from another, the fluctuation diagram technique proposed by Kovátsznay should be used [2]. This technique was developed and adapted to compressible subsonic flows by authors of this paper as well [14–16]. To demonstrate the correct using of the hot-wire technique and FD technique under cryogenic temperature conditions, it is necessary to make sure in the validity of two main laws at least.

First, as it is known, the dependence of the probe resistance $R$ on temperature $T$ is described as:

$$ R = R_s \left[ 1 + \alpha_s (T - T_*) + \beta_s (T - T_*)^2 + \ldots \right] $$

where $\alpha_s$ and $\beta_s$ are the temperature coefficients of resistivity; and $R_s$ is the resistance of the wire at some reference temperature $T_*$. Since the quadratic $\beta_s$ and subsequent terms of the dependence $R(T)$ are rather smaller $\alpha_s$ (usually, for tungsten wires, $\alpha_s = 0.0038 \text{ 1/K}$), it is possible to use its linear in most cases. The resistance dependence on temperature measured for probes with wire diameter 6 and 10 $\mu$m is shown in nondimensional form in Fig. 3. As is clearly seen, there is a good agreement between the measured data and their linear approximation. This confirms a grounded use of linear dependence of the probe resistance on temperature at cryogenic conditions as well.

Second, the most common form of representing the heat transfer law both for subsonic and supersonic speeds at conventional temperature is the King’s law:

$$ \text{Nu} = A + B \text{Re}^n $$
where in general case, the coefficients $A$, $B$, and $n$ are the functions of some flow parameters, probe characteristics, etc. The results of calibrations of the same two hot-wire probes carried out for Mach numbers $M = 0.2$, $0.4$, $0.6$, $0.7$, and $0.8$ are depicted as dependence Nusselt numbers over Reynolds numbers in Fig. 4. One part of calibration points (empty symbols) was obtained at the conventional temperature about 290 K for probe with wire diameter 6 $\mu$m by stagnation pressure changing. The second part was measured for the same Mach numbers at lower temperatures of the flow for probes with wire diameter 6 and 10 $\mu$m. As it can be seen from Fig. 4, calibration curves looking like straight lines are diverging with Mach number in the same way as it was shown by Spangenberg for compressible subsonic flows at conventional temperature [3]. At the same time, there is a good agreement between probe calibrations fulfilled at different temperatures that gives more additional grounds to use the hot-wire technique at cryogenic conditions without some particular limitations.
3 RESULTS AND DISCUSSIONS

The FD measurements were made by using two hot-wire probes of 6 and 10 µm under working conditions which unit Reynolds number $Re_1$ values listed in Table 1.

Each FD was obtained at some different overheating ratio set or, in other words, at different temperatures of the probe. Usually, the number of overheatings $a_w$ was eight (beginning from $a_w = 0.1$ and further with step of 0.1) or more. Therefore, a number of hot-wire data samples was collected. Typical time series of hot-wire output voltage fluctuations of 128 Kb size (upper) obtained at overheating ratio $a_w = 0.8$, Mach number $M = 0.7$, and $T_0 = 150$ K and its frequency spectrum (lower) are given in Fig. 5a. Thus, this signal distribution with skewness and kurtosis factors $k_3 = -0.07$ and $k_4 = 3.02$, respectively, is very close to the Gaussian distribution. Most of signals measured during experiments at different working conditions have the similar kind of distribution that is demonstrated by time series depicted in Figs. 5b and 5c. Nevertheless, it is necessary to mention that there were some samples with quite different distribution. These samples were obtained at limit values of freestream Mach number $M = 0.2$ and 0.7 and overheating ratio $a_w = 0.1$ and 0.8, respectively. Frequency spectra calculated from times series by using fast Fourier transform (FFT) have a shape shown in Fig. 5. As it can be seen, a typical spectrum consists of two distinctive parts. While the low-frequency part has a bell-shaped form, the high-frequency one looks like “white noise” spectrum. Generally, the low-frequency part is spread up to frequencies 300–500 Hz with an obvious maximum at 2–9 Hz.

An example of FD obtained within the broad frequency range (up to 50 kHz) at the conditions listed in Table 2 is shown in Fig. 6. There are given values of mass flow $\langle m \rangle$, total temperature fluctuations $\langle T_0 \rangle$, and correlation coefficient between them $R_{mT_0}$.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>$Re_1/10^4$, 1/m</th>
</tr>
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<tbody>
<tr>
<td>$M \pm 0.001$</td>
<td>$d = 10 \mu m$</td>
</tr>
<tr>
<td>0.2</td>
<td>35.17</td>
</tr>
<tr>
<td>0.4</td>
<td>65.44</td>
</tr>
<tr>
<td>0.6</td>
<td>92.15</td>
</tr>
<tr>
<td>0.7</td>
<td>103.14</td>
</tr>
<tr>
<td>0.8</td>
<td>108.64</td>
</tr>
<tr>
<td>$T_0$, K $\pm 1$</td>
<td>150.1</td>
</tr>
<tr>
<td>$P_0$, atm $\pm 0.02$</td>
<td>3.18</td>
</tr>
</tbody>
</table>
Figure 5  Time series (upper) and frequency spectra (lower) measured at: (a) $M = 0.7$, $T_0 = 150$ K, $a_w = 0.8$; (b) $M = 0.2$, $T_0 = 120$ K, $a_w = 0.1$; and (c) $M = 0.8$, $T_0 = 120$ K, $a_w = 0.8$
Table 2  Mass flow temperature fluctuations, and correlation coefficients at $M = 0.7$; $Re_1 = 56.7 \cdot 10^6$ m$^{-1}$; and $T_0 = 120$ K

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>$(m)$, %</th>
<th>$R_{mT_0}$</th>
<th>$(T_0)$, %</th>
<th>$r_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad</td>
<td>0.82</td>
<td>0.50</td>
<td>0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>0–1 kHz</td>
<td>0.16</td>
<td>−1</td>
<td>0.25</td>
<td>−1.52</td>
</tr>
<tr>
<td>1–50 kHz</td>
<td>0.56</td>
<td>0.76</td>
<td>0.23</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Figure 6  The broad (0–50 kHz) (a) and narrow (1 — 0–1 kHz; and 2 — 1–50 kHz) frequency fluctuation diagrams (b) obtained at $M = 0.7$ and $T_0 = 120$ K

The broad FD has the form of the hyperbola which is typical either for the case of presence in the flow of all three fluctuation modes or for the case of acoustic fluctuations produced by distributed sources of sound [15, 16]. However, if one reconstructs the FD appropriate of some frequency band, a concealed structural feature of flow fluctuations can be discovered. For instance, the FD calculated for low-frequency part of the spectrum looks like a straight line. It means that, most likely, the fluctuations of entropy mode dominate within this frequency band. The FD corresponding to high-frequency part has also hyperbola shape as the broad fluctuation diagram. Most likely, it means that the fluctuations within the frequency band from 1 to 50 kHz have the acoustic nature.

Another example of FD obtained within the broad frequency range (up to 25 kHz) at the conditions listed in Table 3 is shown in Fig. 7. As it is clear from these diagrams, the double reduction of the frequency band does not influence on the form both for broad and narrow FDs essentially. The comparison of fluctuation values $(m)$, $(T_0)$, and correlation coefficients $R_{mT_0}$ is demonstrated in Table 3. The unit Reynolds number $Re_1$ increasing from $41.0 \cdot 10^6$ to $103.1 \times 10^6$ 1/m does not affect on the broad and narrow FD shapes but it results in some change of fluctuation values $(m)$, $(T_0)$, and correlation coefficients $R_{mT_0}$. 

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Figure 7 The broad (0–25 kHz) (a) and narrow (1–0–1 kHz; and 2–1–25 kHz) frequency FDs (b) obtained at $M = 0.7$, $Re_1 = 41.0 \cdot 10^6 \, 1/m$, and $T_0 = 150 \, K$.

Table 3 Mass flow, temperature fluctuations, and correlation coefficients at $M = 0.7$ and $T_0 = 150 \, K$

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>$Re_1/10^6$, $1/m$</th>
<th>$\langle m \rangle$, %</th>
<th>$RmT_0$</th>
<th>$\langle T_0 \rangle$, %</th>
<th>$r_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad</td>
<td>41</td>
<td>0.56</td>
<td>0.41</td>
<td>0.33</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>0.58</td>
<td>0.21</td>
<td>0.24</td>
<td>0.09</td>
</tr>
<tr>
<td>0–1 kHz</td>
<td>41</td>
<td>0.13</td>
<td>−1</td>
<td>0.19</td>
<td>−1.39</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>0.12</td>
<td>−1</td>
<td>0.16</td>
<td>−1.31</td>
</tr>
<tr>
<td>1–24 kHz</td>
<td>41</td>
<td>0.43</td>
<td>0.60</td>
<td>0.23</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>0.55</td>
<td>0.53</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

For instance, relative values of mass flow fluctuation $\langle m \rangle$ were not changed, while total temperature $\langle T_0 \rangle$ values were a bit lowered.

The variation of mass flow fluctuations $\langle m \rangle$ in respect of unit Reynolds number $Re_1$ at fixed freestream Mach number is shown in Fig. 8a (left part). The control of $Re_1$ was mainly provided by means of changing the total temperature of the flow and sometimes by changing the stagnation pressure. As it can be seen, the dependence of fluctuations $\langle m \rangle$ on $Re_1$ is nonmonotonic with some maximum for each Mach number curve. The complete distribution of $\langle m \rangle$ over $Re_1$ is given in the right part of Fig. 8a. It can be seen some weak upward trend of mass flow fluctuations with unit Reynolds number increasing.

In Fig. 8b, the distributions of total temperature fluctuations over unit Reynolds number are presented. The distributions of $\langle T_0 \rangle$ plotted at fixed Mach numbers are looking similarly as $\langle m \rangle$ ones in Fig. 8a. However, the appropriate complete distribution of $\langle T_0 \rangle$ given in the right part of Fig. 8b demonstrates almost constant level of total temperature fluctuations over $Re_1$. 
PROGRESS IN FLIGHT PHYSICS

Figure 8 Mass flow (a) and total temperature (b) fluctuations over unit Reynolds number (for selected $M$ — left and total — right): $1 - M = 0.2; 2 - 0.4; 3 - 0.6; 4 - 0.7; and 5 - M = 0.8$

4 CONCLUDING REMARKS

Investigation of fluctuation structure in the test section of transonic wind tunnel at convenient and cryogenic temperatures of the flow was performed by means of hot-wire anemometer.

1. It was shown the complete applicability of the hot-wire technique, including method of fluctuation diagram, at cryogenic conditions without some particular limitations.

2. The hot-wire measurements allowed to find out that the typical frequency spectrum of flow fluctuations consists of bell-shaped low-frequency and uniform distributed high-frequency parts. There is a marked maximum at frequencies $2-8$ Hz within the low-frequency part of the spectrum.

3. It was discovered that mostly, the fluctuation diagrams corresponded to the low-frequency part of the spectrum have straight line form while the
diagrams reconstructed from the high-frequency part of the spectrum are looking like hyperbolas.

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REFERENCES