Experimental Investigation of Flow Fluctuations around the Cylinder at High Subsonic Velocities

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Abstract
The complex approach to analysis of spectral composition of disturbances and mode diagrams in narrow band allows one determining the type and sources of the most typical fluctuations having place in the flow. The empirical mode decomposition technique together with Hilbert transform was also employed to resolve the spectral composition of fluctuations at a real time. Experiments were performed for circular cylinders 1...4 mm in diameter at freestream Mach number upto M=0.7. Constant current anemometer and single hot-wire probes were used. The new information about intensity and spectral composition of fluctuations obtained before and behind the circular cylinder is presented.

1. Introduction

There are many investigations devoted to studying of vortex shedding behind a bluff body for its complexity in physical phenomena stimulating numerous academic interests. One of simplest and most widespread of such kind cases is a cross streamlining of the circular cylinder. In most cases this is accompanied with flow separation and attachment phenomena which can significantly influence both on aerodynamic performances of the moving body and on the flow parameters downstream.
Studying flow separation from a circular cylinder was performed by Bellhouse and Schultz[1]. They measured the skin friction at Reynolds numbers relevant to the regimes of laminar and turbulent separations. Dwyer and McCroskey[2] employed a thermal film flushed with the surface of a circular cylinder to measure the shear stress on the wall up to the point of separation. They pointed out that the separation point was actually moving on the cylinder, what was further confirmed by the velocity measurements with a double hot-wires probe situated slightly above the surface of the cylinder. Some criteria of unsteady flow separation from circular cylinder in incompressible subsonic flow were worked out[5-8].
The recent water-channel flow visualization experiments[9] gave evidence that flow separation is unsteady and three-dimensional in nature. A study Miau et all[10] indicates as well that the vortex shedding is unsteady and three dimensional and its fundamental frequency is changed with time around some mean value.
With the velocity increasing, around bluff bodies of different configurations is realized the flow with very complicated structure. Some examples of compressible subsonic flows with separation zones and movable contact discontinuities obtained as a result of the numerical integration of the time-dependent equations for an ideal gas are presented[11]. The examples concern a steady annular separation zone on the periodic shedding of unsteady discontinuities from a cylinder in a steady uniform subsonic flow.
The numerical simulation results of cross streamlining of the circular cylinder with laminar compressible flow of perfect gas made at Mach number M = 0.8 and unit Reynolds number Re = 10^5 show that the flow field around the cylinder is greatly nonstationary. Most intensive nonstationary processes take place at rear side of the cylinder due to forming and shedding of vortices from the cylinder surface and their further diffusion in the wake. However, the influence of that nonstationarity propagates also rather far upstream exciting oscillations of gasdynamics parameters [12].

An experimental study of the Mach number influence on vortex shedding past a square cylinder at free stream Mach numbers between 0.15 and 0.91, and at free stream Reynolds numbers between 0.7- 4.2 $*10^5$ was also performed[13]. It was found that the regular vortex shedding is present and the Strouhal number behind the square cylinder is almost constant up to the critical Mach number of about 0.70, but it increases rapidly with further increase of the Mach number.
Results of Fourier analysis as dependence between normalized amplitude of vortex shedding disturbances and Strouhal number in compressible subsonic flow are given in Murthy & Rose study[14]. They have shown that high frequency fluctuations corresponding Strouhal number Sh = 0.18 and nearly independent on flow Mach number were dominated in the wake after the cylinder.
However, the data regarding the fine structure of the immediate neighborhood flow around the circular cylinder and the wake after it at high subsonic are very limited in the literature. In the present work the flow fluctuation structure in the vicinity of the circular cylinder in compressible subsonic flow was studied by means of hot wire anemometer. Some shadow pictures of the cylinder streamlining were also obtained.

2. Experimental background

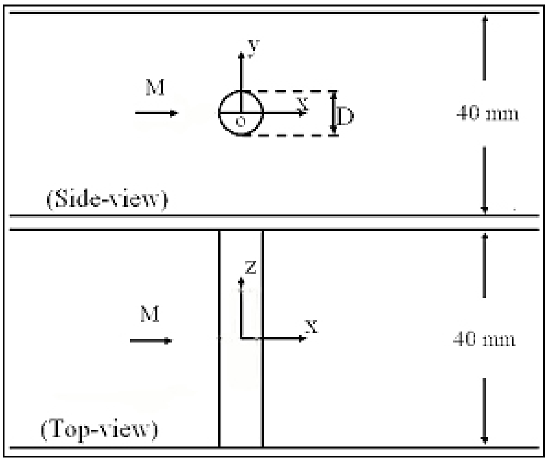


Figure 1:

Experiments were carried out in a blowdown wind tunnel T-325M, whose test section was 40 by 40 mm^2 in cross section. In the empty test section, the maximum Mach number measured was about 0.8 with the fluctuation intensity less than 0.2%. During experiments freestream Mach number can be continuously adjusted within the range from 0.3 upto 0.8 by means of special diaphragm placed past the test section. The circular cylinders employed for the present study were 4, 2 and 1*mm* in diameter and 40 *mm* in length. The cylinder was spanned between two sidewalls of the test section. Shown in Figure 1 is a schematic drawing of the present flow configuration and the coordinate system employed.
In the present study, the Reynolds number *Re* is defined based on the diameter of the cylinder, *D*, and the incoming velocity, U_0, The experimental data reported in this paper were obtained at $Re = 2.05 - 8.1 \times 10^4$. Constant current anemometer homemade at ITAM and hot-wire probes with golden plated tungsten sensitive elements 6 mkm in dia and 1.2 mm length have been used. The frequency range of the anemometer is provided upto 200 kHz at all overheat parameters. The hot-wire output was digitized by two 14-bit analog-to-digital converters with the sampling rate 400 kHz. After converting the analog signal to digital type the data were fed into the PC for further processing.

2.1. Experimental technique

It is known, that the voltage across the hot-wire probe placed in a flow depends on its velocity u, total temperature T_0 and density ρ:

$$E = E(\rho, u, T_0). \qquad (1)$$

After logarithmic differentiation and some transformations the equation (1) comes to the following form, a non-dimensional expression concerning instantaneous changes of voltage fluctuations on the probe with instantaneous fluctuations of velocity u, density ρ and total temperature T_0

$$\frac{e'}{e} = F_\rho \frac{\rho'}{\rho} + F_u \frac{u'}{u} + G \frac{T_0'}{T_0} , \quad (2)$$

where F_r, F_u, G are the sensitivity coefficients to density, velocity and total temperature[15].
Usually in experiments the root mean square voltage from output of anemometer is measured, that is why equation (2) after squaring, averaging and dividing by G^2, under condition $F_u = F_\rho = F$ and $r_\rho = r_u = r$, can be written as following

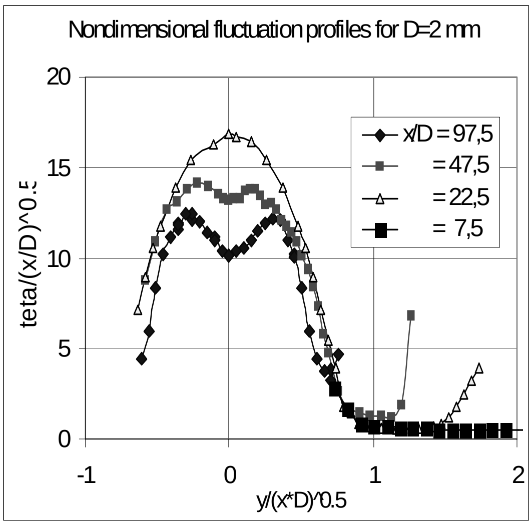
$$\vartheta^2 = r^2 < m >^2 - 2rR_{mT0} <m><T_0> + <T_0>^2, \quad (3)$$

where F is the sensitivity to mass flow $m = \rho\, u$, R_{mT0} is the correlation coefficient and r is the relative sensitivity coefficient respectively. The equation (3) has a form of hyperbola which is well-known at supersonic flows as fluctuation diagram[16, 17]. Kovasznay showed that the diagrams can have quite a definite shape for some specific cases when fluctuations of only one type (vorticity, entropy or acoustic modes) are present in the flow[16]. The fluctuation diagram (3) can be used at high subsonic velocities as well. It was shown[16, 17] that in this case the fluctuation diagrams for vorticity and entropy modes are the same as at supersonic speeds, but it has a special form for acoustic mode

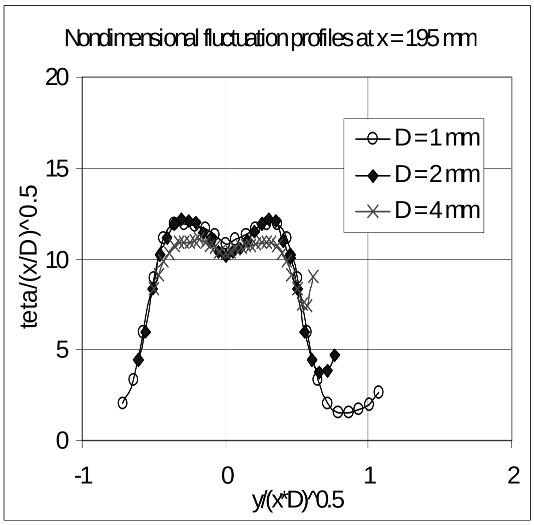
$$\vartheta = <\rho> |\alpha(\kappa - 1)(1+ \mathrm{M} \cos\chi) - r(1+ \mathrm{M}^{-1} \cos\chi)|, \quad (4)$$

where κ is the ratio of specific heats, M is the Mach number, $\alpha=1/(1+(\kappa-1)/2\times \mathrm{M}^2)$ and χ is the angle between the flow velocity vector and the direction of acoustic waves propagation. The fluctuation diagram (4) corresponds to the plane sound waves with $\chi = \chi_0 =$ const and point source of acoustic disturbances with $\chi =$ var. It ought to accentuate the fluctuation diagram looks like letter “V” in both cases.
A number of sources of sound distributed over the surface is a case very often encountered in practice and therefore it is of interest. In order to consider the hot-wire probe response to acoustic disturbances in this situation it is necessary to compute an integral over the surface by using (4)[18, 19].

3. Results and discussions



a)



b)

Figure 2: Nondimensional fluctuation profiles measured at M=0.7

Figure 2a presents nondimensional distributions of fluctuations (variable ϑ, see (3) and (4)) across the wake behind the cylinder with D=2 mm (fluctuations were measured within wide frequency band, upto 200 kHz). The comparison of profiles demonstrates that the wake state in the vicinity of the cylinder is far from self-preserving form. So, at x/D = 7.5 the fluctuation profile has one prominent maximum. With developing of the wake domnstream its shape is changed and the profile becomes two-humped. However, the fluctuation profiles measured within the narrow frequency band at the frequency corresponding vortex shedding behind cylinder have two-humped shape even in the immediate neighborhood of the cylinder. Figure 2b shows that distributions of nondimensional fluctuations across the wake for different cylinders with D=1, 2 and 4 mm (measured within wide frequency band) have a form close to similar one, especially it is related to cylinders with D=1 and 2 mm.

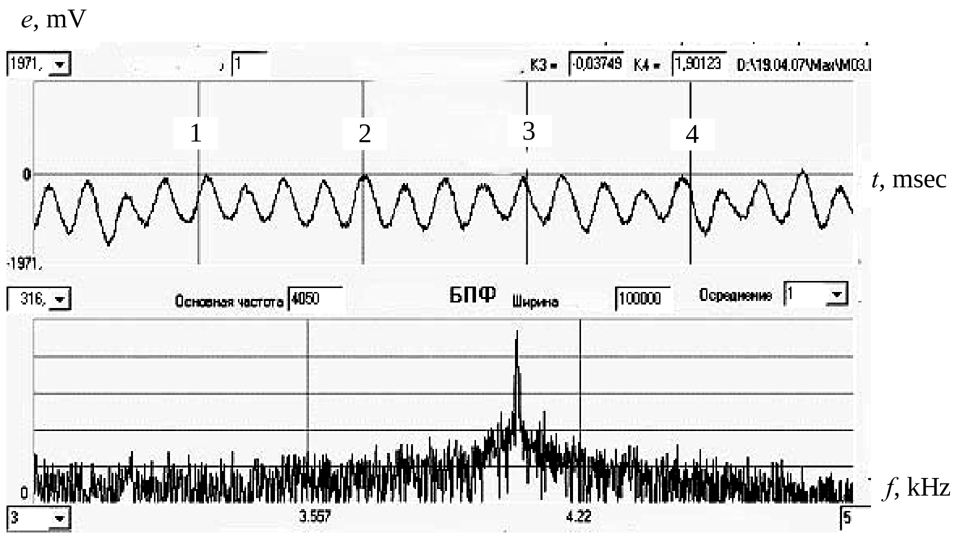


Figure 3: Time series (above) and frequency spectrum (below) obtained for D = 4 mm at x = 15 mm at Mach number M=0.30

Time series of the hot wire output signal (above) and its frequency spectrum (below) obtained downstream of the cylinder D = 4 mm at Mach number M=0.30 are given in the Figure 3. Hot wire probe position was at y = 10 mm and x = 15 mm, according to the Figure 1. It is seen that the flow behind the cylinder is modulated in almost sinusoidal way with fundamental frequency f = 4.05 kHz. The similar results were obtained for the same probe position for different freestream Mach numbers M = 0.35 ÷ 0.7 with step 0.05. Increasing of the Mach number results in growing fundamental frequency f with simultaneous decreasing of the intensity of fluctuations. The shape of time series was kept similar to as shown Figure 3.

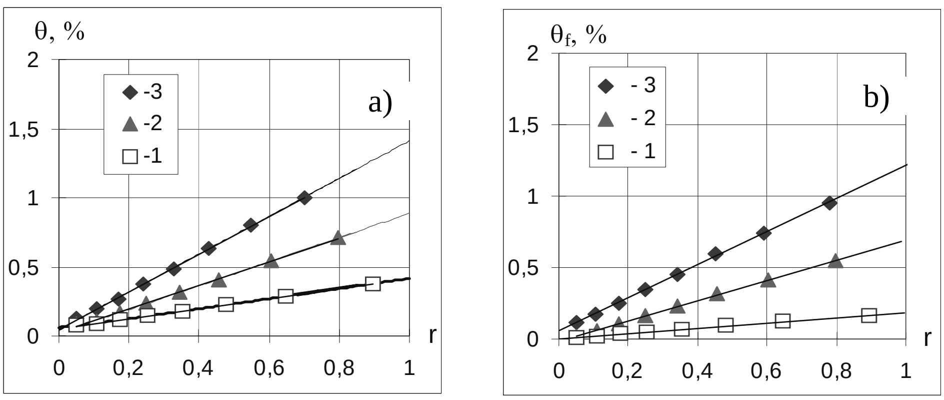


Figure 4: Fluctuation diagrams. Cylinder D = 4 mm, x = 15 mm
a) – total; b) – narrow frequency band, D*f* = 0.1 kHz

Table 1

		$<m_f>$, %	$<T_{of}>$, %	$R_{mT_{of}}$	y, mm	M	*f*, kHz
a)	1	0.37	0.06	-0.64	14	0.50	0…200
	2	0.88	0.06	-1	10	0.50	0…200
	3	1.36	0.04	-1	10	0.30	0…200
b)	1	0.18	0.003	-1	14	0.50	6.44
	2	0.71	0.01	-1	10	0.50	6.44
	3	1.16	0.04	-1	10	0.30	4.05

Total (f = 0…200 kHz) and narrow band (Δf = 0.1 kHz) fluctuation diagrams in Figure 4a, b and data of Table 1 confirm this assumption in detail. All fluctuation diagrams have close to linear shape and mass flow fluctuations <m> exceed the total temperature fluctuations $\langle T_0 \rangle$ a few times. It is worth to mention the intensity of fluctuations within the wake in narrow band at M =0.3 and 0.5 contains about 80% of total fluctuations intensity what is in concordance with shape of time series shape in Figure 3. Moving hot wire probe out to the wake boundary from y = 10 to y = 14 mm results in decreasing total fluctuations <m> level at M =0.5 almost twice and in narrow band four times. At the same time, the fundamental frequency kept the same value.

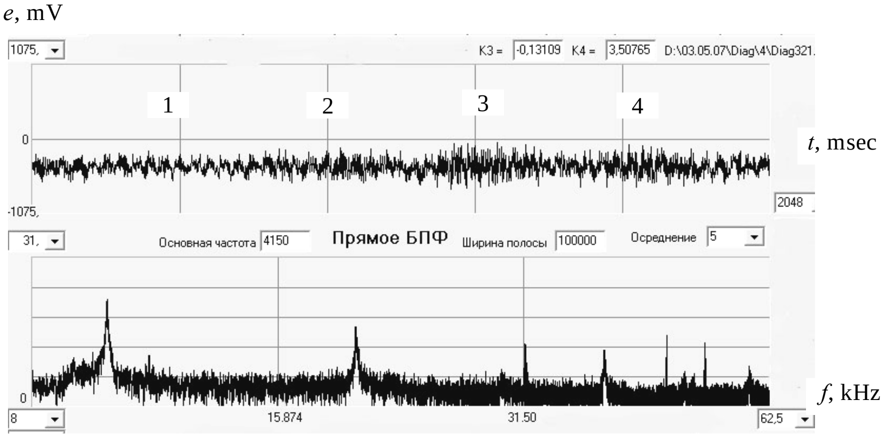


Figure 5: Time series (above) and frequency spectrum (below) obtained at
x = -10 mm at freestream Mach number M=0.608.

Time series and frequency spectra of the hot wire output signal upstream of the cylinder D = 4 mm at x = - 10 mm for Mach numbers M = 0.30 ÷ 0.7 with step 0.05 were obtained as well. However, the nature of time series was significantly changed. The flow upstream the cylinder is not so much modulated as downstream and the intensity of fluctuations is decreased dramatically. Besides, the fundamental frequencies were weakly visible within frequency spectra with the exception of regimes at M = 0.608 and 0.68.

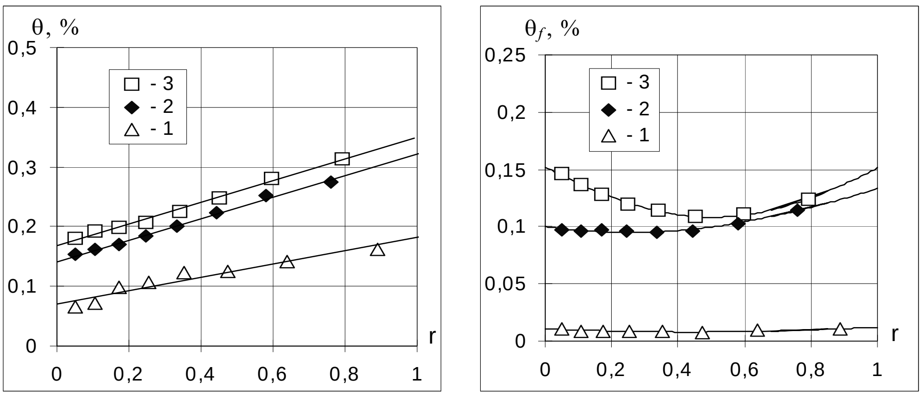


Figure 6: Fluctuation diagrams. Cylinder D = 4 mm, x = -10 mm
a) – total; b) – narrow frequency band, Δf = 0.1 kHz

Table 2

		$\langle m_f \rangle$. %	$\langle T_{of} \rangle$. %	$R_{mT_{of}}$	y. mm	M	f. kHz
a)	1	0.11	0.07	-1	12	0.684	0…200
	2	0.18	0.14	-1	14	0.608	0…200
	3	0.23	0.17	-0.54	4	0.608	0…200
b)	1	0.02	0.012	0.76	12	0.684	11.03
	2	0.12	0.10	0.32	14	0.608	9.86
	3	0.21	0.15	0.70	4	0.608	9.89

There was just very low peak in spectrum comparable with background noise at M = 0.68. In contrary, some kind of flow resonance arouse at Mach number M = 0.608. This resonance was suppressed strongly with small increasing or decreasing of freestream Mach number.

The example of time series (above) and its frequency spectrum (below) corresponding to freestream Mach number M=0.608, y = 14 mm and x = -10 mm is depicted in Figure 5. It is seen that the flow behind the cylinder is modulated not so strongly even at M = 0.608 as it was at probe position x = 15 mm, behind cylinder. Moreover, the frequency spectrum contains not only fundamental frequency *f* = 9.86 kHz but a few its harmonics as well.

Total and narrow band fluctuation diagrams are given in Figure 6a, b respectively and data of fluctuation intensities in Table 2. All total fluctuation diagrams have close to linear shape as mentioned above for downstream probe position but at the same time the value of total fluctuations $<T_0>$ was grown and, in contrary, mass flow fluctuations $<m>$ were lowered. Moving hot wire probe inside the wake from y = 14 to y = 4 mm results in some growing of total fluctuations $<m>$ level at M =0.608. At the same time, the narrow band fluctuation diagrams at fundamental frequency are transformed to hyperbola form and main portion of intensity fluctuations belongs to the first harmonic both at y = 4 and 14 mm. The transformation of diagrams to hyperbolic form means that diagrams correspond to case of sound sources distributed over some surface or line[18, 19]. Most likely, it can be the stagnation area behind the cylinder. It is confirmed by flow visualization in Figure 7, see below. Increasing of Mach number upto M = 0.68 gives some lowering of total fluctuations level and an immense suppression of fluctuations within narrow band at some fundamental frequency f = 11.03 kHz.

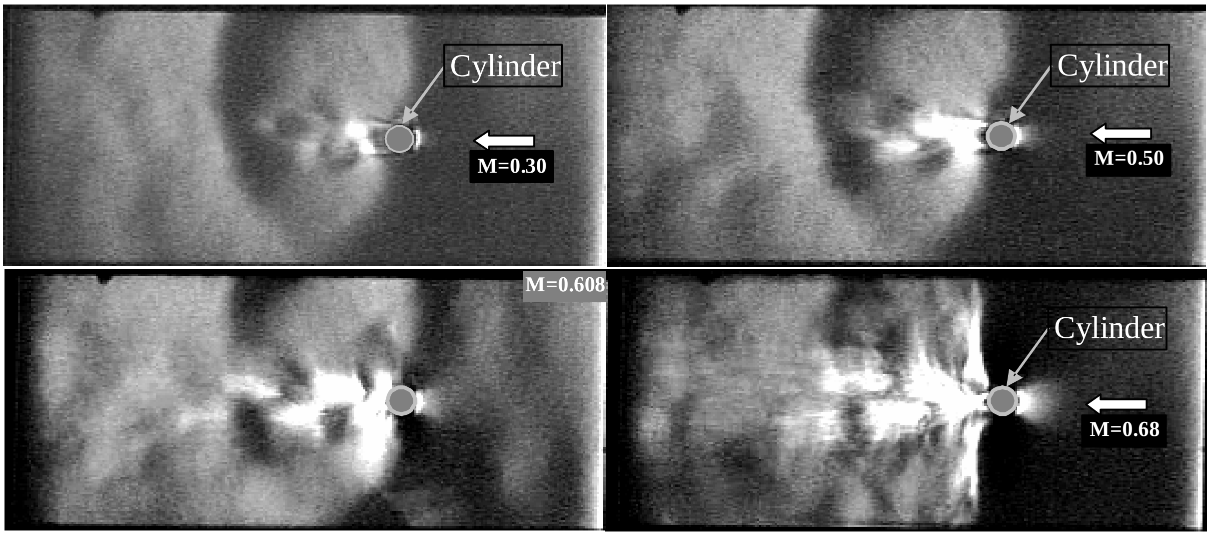


Figure 7: The visualization pictures of the cylinder streamlining at different freestream Mach numbers

The figure 7 presents the visualization picture of the flow structure taking place in compressible subsonic flow at different Mach numbers. It is clear seen the formation of vortex shedding at M = 0.3 and 0.5. At Mach number M = 0.608, there is observed both the vortex shedding downstream of the cylinder and upstream propagation of the sound waves visible in the picture in the form of different density areas. With achievement M = 0.68 there is accumulated a set of almost normal pressure waves which are placed just past the cylinder. These pressure waves are collected and traveled a bit back and forth. Throughout, they are an obstacle to upstream sound propagation what was earlier demonstrated by fluctuation diagram as well.

4. Concluding remarks

Investigation of fluctuations around circular cylinder at high subsonic flow velocities was performed by means of hot-wire anemometer. It allows one to obtain not only information about fluctuations level around cylinder, but also to take some additional information regarding the structure of the sources generating these fluctuations.

The hot-wire technique allows to find out the detailed data on a nature of compressible subsonic streamlining of the cylinder. It was discovered that at Mach number M = 0.608 some kind of flow resonance around the cylinder is appeared which is suppressed rapidly with even small deviation of freestream Mach number to a greater or lesser side.

It was found out that it takes place an immense suppression of fluctuations at M = 0.68 corresponding to fundamental frequency f = 11.03 kHz due to accumulation past the cylinder a set of almost normal pressure waves obstructing the passage of acoustics upstream the flow.

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