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High-frequency fluidic oscillator

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ABSTRACT

There is a number of potential applications for no-moving-part fluidic oscillators if they could oscillate in the kilohertz range and yet be of convenient, i.e. not too small size. The solution offered in this paper is based on a new oscillation principle, with stationary rotating vortex inside the chamber bounded by two attachment walls. The response to gradually increasing air flow rate has shown three distinct regimes, of prime importance being the constant Strouhal number regime at small Reynolds numbers from Re ~2600 to Re ~6000, oscillating at f = 1.7 kHz and f ~ 5 kHz, respectively. Even higher frequency f ~ 8.2 kHz was found in another, higher Re regime.

1. Introduction

1.1. Fluidic oscillators

Devices generating periodic oscillation of fluid flow without action of any moving or deformed components are recently increasingly often used in numerous applications in which they increase process effectiveness. In particular, they are used in active control of flow separation and transition into turbulence [1] on bodies exposed to fluid flow. Employed in enhancing heat and mass transfer processes the oscillating jet destruct boundary layers which act in steady regimes as hindrance to the transport phenomena. Important fact is simplicity of the oscillators, essentially nothing more than just specially shaped cavities through which the supplied fluid flows. Consequence of the simplicity is reliability and low cost.

In principle, fluidic oscillators operate by utilising hydrodynamic instabilities appearing in some fluid flows. The instability is usually amplified by providing a suitable opportunity for a negative feedback in the fluid flow—such as tubes connecting output terminal of a fluidic amplifier with its input, as originally patented by Warren [2]. Working with fluid (either gas or liquid) makes fluidic oscillator advantageous in those applications where fluids are handled anyway. The oscillator is driven by taking a small percentage of energy of the supplied fluid. It thus does not need any external energy input (such as electric driving, which would be dangerous especially in a system handling water). Because of their solid, fixed geometry the fluidic oscillators do not suffer by reliability problems encountered by devices with mechanical components and linkages, which may get stuck, may have their springs or membranes broken, their screws getting free, etc.

Interesting recent applications of fluidic oscillators were described in refs. [3–5] as passive micromixers and microreactors for chemical engineering. The activities devoted to continuing developments of fluidic oscillators have resulted, e.g., in [6], to derivation of universal dependence of oscillation frequency f on time-mean Reynolds number of flow

$$\mathrm{Re} = \frac{\mathrm{b\,w}}{\nu} \qquad (1)$$

- calculated from the conditions in the main (supply) nozzle of the amplifier, i.e., its width b [m], its local flow velocity w [m/s], and fluid kinematic viscosity ν [m^2/s].

Typical present-day fluidic oscillator consists of two basic parts: a fluidic jet-deflection diverter amplifier on one hand and feedback loop tubes (connected to the amplifier control and output terminals) on the other hand. There are some specialised geometry designs of amplifiers for oscillators, e.g., with the step-shaped attachment walls [7], departing from the standard bistable amplifier designs. Nevertheless oscillators based on the previously developed high-performance amplifiers are still widespread.

Another family of fluidic oscillators was introduced recently in [8]. It is also based on standard bistable amplifier geometry, but instead of the feedback loops its oscillation effect is achieved by use of acoustic waves propagating back and forth in a resonator channel. On its return the pressure wave acts on the main jet flow in an amplifier and deflects it—but this deflection is only

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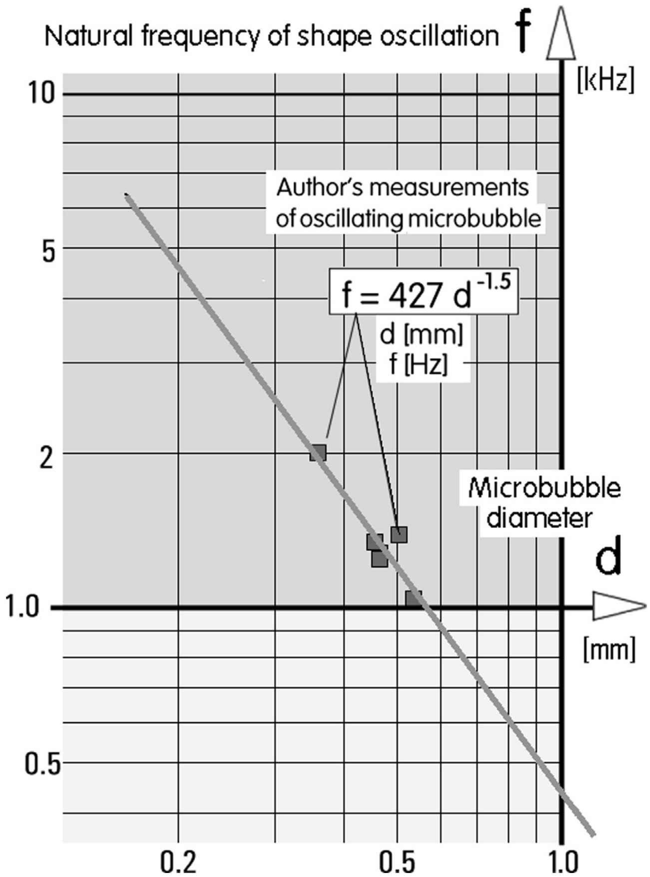

Fig. 1. Natural frequency of air microbubbles in water [5]. One important recent use of fluidic oscillators is producing very small gas bubbles by oscillating inlet gas flow into an aerator. For efficient action the oscillation is to be applied in the kilohertz-range natural resonant frequency of bubbles.

temporary since the opening of the control nozzle to atmosphere on this second side suppresses the corresponding Coanda effect.

In oscillators with the feedback loops the tube lengths are the key parameter determining the oscillation frequency f [Hz]—which, however, is also dependent on the magnitude of the supplied fluid flow rate, because these oscillators (as is typical in general for periodic phenomena in flows within solid, non-variable geometry) tend to keep a more or less constant value of Strouhal number

$$Sh = \frac{f\,b}{w} \tag{2}$$

Typical range of operating frequencies of present-day oscillators is from f ~50 Hz to ~300 Hz obtained with an amplifier of typical outer size 20 mm–200 mm.

Somewhat higher frequencies, let us say up to f ~500 Hz—may be obtained with the resonator designs [8]. Because speed of sound in typical applications (with not significantly varied gas temperature) does not vary, the characteristic property of these oscillators is their constant frequency of oscillation. Nevertheless the upper limit of frequencies is still below the kilohertz range. Any higher frequency requires making the oscillator by special microfabrication techniques due to inevitable small size—and the small size also necessitates working with much smaller flowrates than would be desirable in typical applications.

1.2. Requests for high frequency

As mentioned above, typical frequency range of fluidic oscillators has an upper limit near to 0.5 kHz. This has sufficed for most applications, but recently arose quite frequently requirements of operation at significantly higher frequencies, in the order of kilohertzs. These are not easy to obtain with the standard oscillator configurations, especially if the device is simultaneously demanded to be not very small.

Such a demand for high-frequency oscillators emerged recently in generation of small gas bubbles in liquids [9,17]. Very small gas bubbles, of diameter less than 1 mm, are called microbubbles. They offer numerous advantages in applications over the standard larger bubbles, especially in chemical and process engineering. One of the approaches to microbubble generation is based on the idea of fragmentation of larger bubbles by oscillating the gas supply flow. To be effective, the oscillation is to be applied at the natural resonant frequencies [10] of shape variations—or at integer multiples. These natural frequencies are quite high. Fig. 1 presents the measured dependence of the natural frequency on the microbubble diameter d, obtained by author from evaluation of high-speed camera shape change images. To be tuned to the microbubble oscillatory motions, the oscillator frequencies should be in the grey upper part of the diagram—at the power-law line fit to the experimental data. Clearly apparent is desirability of frequencies from f ~ 1 kHz to ~ 8 kHz needed to obtain microbubbles of the size between $d = 0.5$ mm and $d \sim 0.15$ mm

Another request for high frequency fluidic oscillators comes nowadays from the control of flows past objects like, e.g., turbine blades [11,12]. The control by oscillating jets was demonstrated to be able to suppress separation of the flow from surfaces and also eliminate transition into turbulence. Literature [11,12] describes demonstration of restoring the aerodynamic performance of a stalled turbine blade by pulsating jets. Basic feasibility tests are usually made in aerodynamic laboratories [13] on "hump"-shaped models and are mostly performed at rather low Strouhal numbers, corresponding to the natural frequency of vortex shedding from the hump surface. Although these results are satisfactory, it is important to note that in the authoritative paper by Glezer et al. [14] came a warning that these test frequencies may have dangerous consequences. They are likely to amplify unsteady aerodynamic forces on blades or wings. To avoid the problem, it is recommended to use driving frequencies much higher, at least by a decimal order of magnitude. This, unfortunately, means frequencies at or already beyond the upper limits of the range obtainable with the standard fluidic oscillators. It is especially the case with oscillators of the feedback loops type—even if the loop channels are short and the

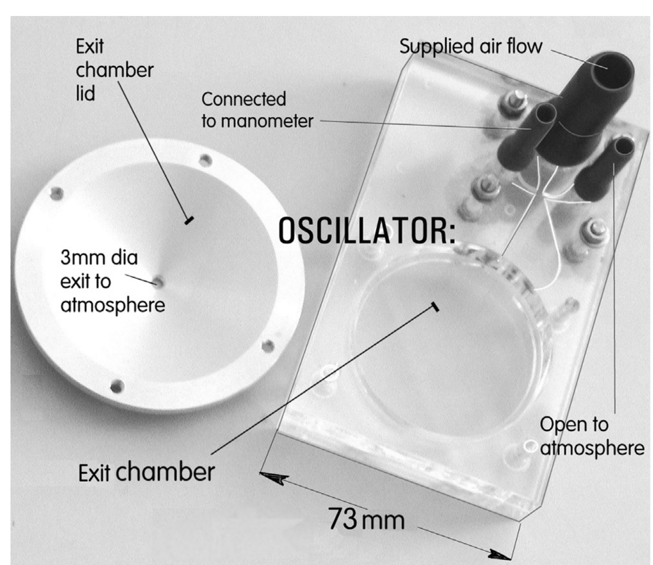

Fig. 2. Photograph of the high-frequency oscillator and the circular exit chamber.