Chapter 12
Introduction to the Synthetic Jet Flow Control and Drag Reduction Techniques

Milan Matejka

12.1 Introduction

Synthetic jet—alternating blowing and suction—is a well-known shear layer active flow control technique. By means of the synthetic jet, it is possible to lower drag, to increase lift, or to intensify heat transfer in a wide range of different applications like airplanes, cars, compressors, turbines, etc. One of the first who showed that turbulent boundary layer separation can be controlled by alternating blowing and suction was Seifert et al. (1993). Chen et al. (1999) focused on the increase of mixing to intensify heat transfer, and Smith and Glezer (2002) demonstrated the possibility to use synthetic jet for jet vectoring. An important advantage of the synthetic jet, comparing to a conventional blowing or suction, is a significantly lower value of the supplied momentum needed for the same effect (Seifert et al. 1993).

The efficiency of the flow control by means of a synthetic jet depends on a correct design of the synthetic jet generator which influences creation of vortex structures. The design of the synthetic jet generator must be made in relation to the character of the flow field. The frequency of the synthetic jet should correspond to the natural vortex shedding frequency to influence separation or mixing process in the right way. This can be described like a change of the rate of vortex structures splicing. Several approaches can be used to influence the rate of vortex's structures splicing by the synthetic jet. The first case is when the exciting frequency of the synthetic jet corresponds to the natural vortex shedding frequency. Another possibility is the application of high-frequency synthetic jet with amplitude modulation (Matejka et al. 2009, 2011). Amplitude modulation is used to generate lower frequencies, which agrees with the natural vortex shedding frequency. Many authors used

M. Matejka (✉)
Researcher, Czech Technical University in Prague (CTU), Faculty of Mechanical Engineering (FME), Technicka 4, 166 07, Prague, Czech Republic
e-mail: milanmatejka@hotamil.com

Fig. 12.1 The synthetic jet
generator
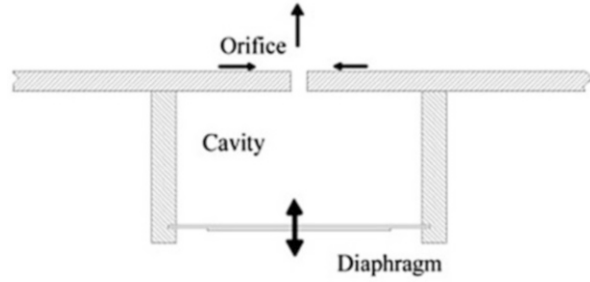
exciting frequency of the synthetic jet much higher comparing to frequency of the natural vortex shedding frequency. This case was explained by Dandois et al. (2007).

The synthetic jet is creating vortex structures. These vortex structures originate from the interaction of the boundary layer (main flow) with pulsating stream from output orifice of the synthetic jet generator (see Fig. 12.1). The flow control should be done with minimum input power, so the synthetic jet generator should be operated on its resonant frequency. In case of resonant frequency, the velocity of the synthetic jet is maximized. Preliminary design of the synthetic jet generator can be done using lumped element modeling (LEM) (Gallas et al. 2002). LEM is based on analogy between electrical and acoustic domain, which corresponds to the synthetic jet actuator. The main assumption of LEM is that the characteristic length scales of the governing physical phenomena are larger than the geometric dimension. In this case, the acoustic wavelength must be significantly greater than the size of the synthetic jet generator.

12.2 Frequency and Intensity of the Synthetic Jet

Generally, the reason of drag reduction is in creation of vortex structures (transversal or longitudinal vortexes) which influence the character of the flow (boundary layer).

Effective application of the synthetic jet in the flow field without shock waves is formation of transversal vortex structures (Fig. 12.2). Creation of these structures must have corresponding frequency and size to influence the flow field in positive way—reducing of drag.

On the other hand, effective application of the synthetic jet in high-speed flow (with shock waves) is creation of longitudinal vortexes (Fig. 12.3). This is because creations of transversal vortexes occur arising of new shock waves, which negatively influence the flow field. Longitudinal vortexes significantly reduce the separation caused by shock wave and reduced value of drag coefficient. Interaction of high-frequency synthetic jet (which frequency is significantly higher than shedding frequency of free stream) with boundary layer is similar to interaction of continuous jet with boundary layer. Both synthetic and continuous jets can be used to generate longitudinal vortex structures. In publication (Doerffer et al. 2010), authors show

Fig. 12.2 LES simulation, synthetic jet actuation—transversal vortex (Dandois et al. 2007)

Fig. 12.3 Normal shock interaction controlled by 3D devices, creation of longitudinal vortex structures (Babinsky and Ogawa 2008)

in flow field with shock wave generation of longitudinal vortex structures using continuous jet. An important variable is the inclination of the jet to the surface and to the main flow field.

12.2.1 Frequency and Intensity of the Synthetic Jet

The efficiency of the flow control under influence of the synthetic jet strongly depends particularly on two variables. The first variable is the exciting frequency of the synthetic jet f, which should correspond to the vortex shedding frequency of the flow. Vortex shedding frequency of the flow can be measured or can be roughly calculated from nondimensional frequency F^+:

$$F^+ = \frac{f \times X_{te}}{U_\infty} \tag{12.1}$$

Optional value of nondimensional frequency F^+ can be set at value of 1.2 (Greenblatt et al. 2005). This optimal value is also connected with the intensity of the synthetic jet, which is defined by unsteady momentum coefficient c_μ. The value of the momentum coefficient c_μ influences the intensity of the synthetic jet as well:

$$c_\mu = \frac{\rho_o \times u_o'^2 \times h}{1/2 \times \rho_\infty \times U_\infty^2 \times l} \qquad (12.2)$$

where u_o' is mean velocity (in meaning of time and spatially) in output orifice of synthetic jet generator,

$$u_o' = \frac{\sqrt{\int_0^h \overline{u}_o(y)^2 dy}}{h} \qquad (12.3)$$

and time mean velocity (positive part of period T)

$$\overline{u}_o = \frac{2}{T} \times \int_0^{\frac{T}{2}} u_o(t) \times dt = \cdots = \frac{1}{T} U_{max} \int_0^{T/2} \sin(\omega t_s)\, dt_s = \frac{U_{max}}{\pi} \qquad (12.4)$$

Frequency f of the synthetic jet can be expressed from Eq. (12.1). Value of X_{te} is the distance from output orifice of the synthetic jet position to the point of reattachment—mixing length. High-output velocity of the synthetic jet can cause negative effects to the flow field, so the maximum output velocity from the synthetic jet generator should be comparable to the mean flow velocity or lower. Now, size of output orifice h from Eq. (12.2) can be calculated. Minimal value of momentum coefficient c_μ is associated with the frequency f of the synthetic jet. Optimal value of nondimensional frequency F^+ in many cases matches to the value about 1.2 (Greenblatt et al. 2005; Smith and Glezer 2002). Then minimal value of momentum coefficient c_μ corresponding to this optimal value of nondimensional frequency F^+ is about 0.2% (Greenblatt et al. 2005; see Fig. 12.4).

12.2.2 Criteria of Existence of the Synthetic Jet

The next important point is to check if the synthetic jet, defined above, fulfills criteria of existence of the synthetic jet (Trávníček et al. 2012; Holman et al. 2005; Timchenko et al. 2004). Criteria of existence of the synthetic jet is defined by nondimensional numbers: Strouhal number of output orifice of the synthetic jet generator Sh_o (12.5), Reynolds number of output orifice of the synthetic jet generator Re_o (12.6), and Stokes number of output orifice of the synthetic jet generator St_o (12.7).

Fig. 12.4 The dependence of drag coefficient CD on the value of momentum coefficient c_μ and nondimensional frequency F^+ (Greenblatt et al. 2005)
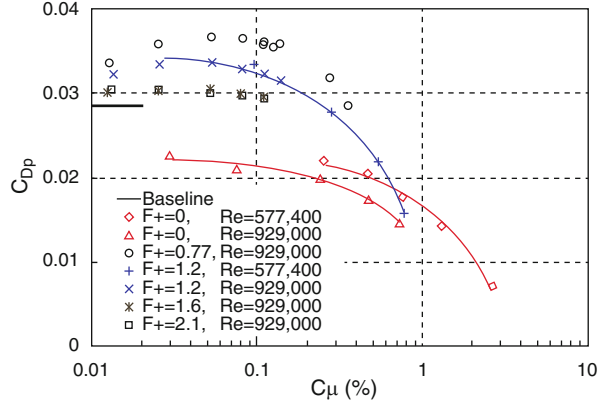
$$\mathrm{Sh}_o = \frac{f \times D}{\overline{u}_o} = \frac{D}{T \times \overline{u}_o} = \frac{D}{L_O} = \frac{2 \times f \times D}{\overline{U}} = \frac{\mathrm{Sh}_H}{\pi} \tag{12.5}$$

$$\mathrm{Re}_o = \frac{\overline{u}_o \times D}{\nu} = \frac{\mathrm{Re}_H}{2} = \frac{\mathrm{Re}_{\max}}{\pi} = \frac{\mathrm{Re}_L}{L_O} \times D \tag{12.6}$$

$$\mathrm{St}_H = \sqrt{\mathrm{Sh}_H \times \mathrm{Re}_H} \tag{12.7}$$

Figure 12.5 shows the area of existence of the synthetic jet. Value of Strouhal number of output orifice Sh_o must be smaller than about 2 (value of L_o/D must be greater than 0.5), and Reynolds number Re_H must be greater than about 50. Stokes number St influences the range of the synthetic jet (Brouckova et al. 2011) and shape of velocity profile in output orifice of the synthetic jet generator (Nae 2000).

12.3   Design of the Synthetic Jet Generator

The synthetic jet generator should be designed with respect to the frequency of the synthetic jet (see previous chapter) and minimum power input of the actuator. Minimum power and maximum intensity of the synthetic jet can be obtained in resonant frequencies of the synthetic jet generator.

Preliminary design of the synthetic jet generator can be done using lumped element modeling (LEM) (Gallas et al. 2002). LEM is based on analogy between electrical and acoustic domain. Schema from Fig. 12.1 represents the synthetic jet generator converted to electrical circuit (see Fig. 12.6).
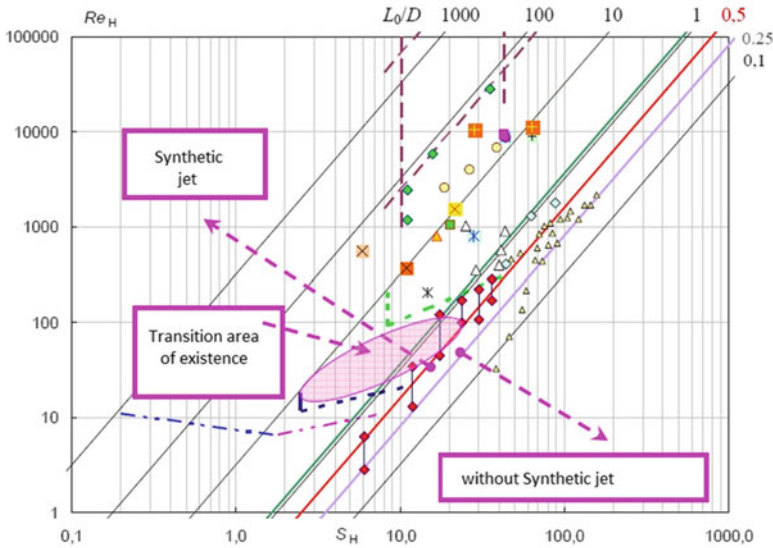
Fig. 12.5 Criteria of existence of the synthetic jet (Trávníček et al. 2012)
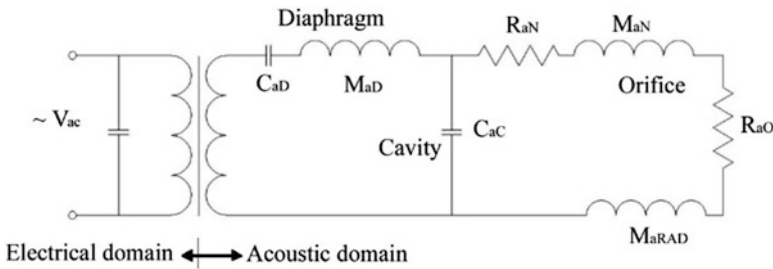

Fig. 12.6 Lumped element mode—equivalent electrical circuit

Individual parts of the synthetic jet generator components (diaphragm/membrane, cavity, and orifice) are modeled as elements of an equivalent electrical circuit using conjugate power variables. Those variables (C_{aD}, diaphragm short-circuit acoustic compliance; M_{aD}, diaphragm acoustic mass; C_{aC}, cavity acoustic compliance; M_{aN}, orifice acoustic mass; M_{aRad}, orifice acoustic radiation mass; R_{aD}, diaphragm acoustic resistance; R_{aN}, viscous orifice acoustic resistance; and $R_{aO,}$ nonlinear orifice acoustic resistance) are expressed using electroacoustic theory (Morse and Ingard 1968; Gallas et al. 2003). Value of variables depends on geometry of generator and material properties. Impedance of electrical circuit can be calculated from abovementioned values. Impedance Z, expressed from those values, is used to calculate volume flow rate in output orifice, (12.8) and (12.9).

$$\frac{U_V}{Z} = \frac{\dot{V}}{\varphi} \tag{12.8}$$

$$\mathrm{da} = \frac{\varphi}{C_{\mathrm{aD}}} = \frac{\Delta V}{U_V} \tag{12.9}$$

where U_v is applied voltage, V is total flow rate, and φ is electroacoustic turns ratio. The next step is expression of flow rate volume V orifice in output orifice of the synthetic jet generator depending on exciting frequency f. All variables as flow rate in output orifice, voltage, impedance, and effective acoustic coefficient da (12.9) are functions of $s = \omega j$, where $\omega = 2\pi f$. Thereafter the related equation is

$$\frac{\dot{V}_{\mathrm{orifice}}(s)}{U_V(s)} = \frac{\mathrm{da}(s)}{a_4 \times s^4 + a_3 \times s^3 + a_2 \times s^2 + a_1 \times s + 1} \tag{12.10}$$

where "a_i" are constants determined via simple algebraic expression as a function of geometry and material properties (C_{aD}, M_{aD}, C_{aC} ...). The output velocity can be calculated from size of area of output orifice of the synthetic jet generator and flow rate in output orifice V_{orifice}. Amplitude-frequency characteristic, dependence of velocity on exciting frequency, is shown in Fig. 12.7. One or two resonant frequencies from amplitude-frequency characteristic are obtained. Output velocity of the synthetic jet at these resonant frequencies reaches the maximum value.

Generator of the synthetic jet is suitable to use in resonant frequency, because of minimal power input comparing to power output. Then resonant frequency of the synthetic jet generator should correspond to the frequency of vortex shedding phenomena (see previous chapter). Change of dimension (size of cavity, diameter of
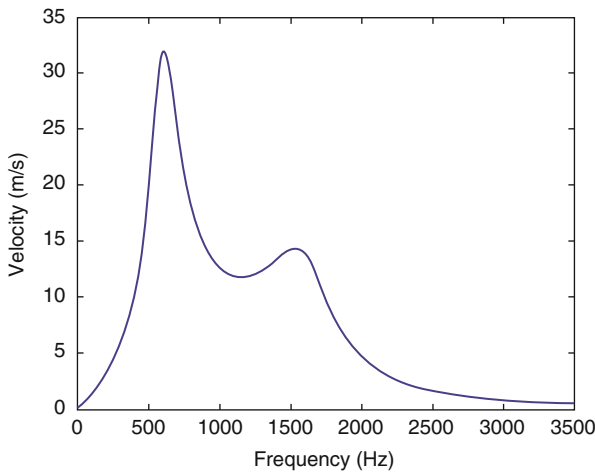
Fig. 12.7 Amplitude-frequency characteristic, dependence of velocity to exciting frequency

membrane, etc.) of the synthetic jet generator must be done, if resonant frequency of the synthetic jet generator does not correspond to the frequency of vortex shedding phenomena.

12.4 Efficiency of Flow Control

The most common goal when applying synthetic jet flow control is to minimize total losses. The energy required for application of synthetic jet needs to be included as well.

To express the local loss coefficient of total pressure can be used to formulate of the overall effectiveness of the synthetic jet control of the boundary layer, which is defined by

$$\xi(i) = \frac{p_{\text{tot1}} - p_{\text{tot2}}(i)}{p_{\text{dyn1}}} \tag{12.11}$$

where p_{tot1} is total pressure in cross section before the model, p_{tot2} total pressure in probe position behind the model, and p_{dyn1} is dynamic pressure in cross section before the model. Total pressure is measured by traversing total pressure probe or total pressure rake probe (Fig. 12.8).

Drag coefficient or total loss coefficient is defined as

$$c_D = \frac{2 \times F}{\rho \times A \times U_\infty} = \xi_{\text{tot}} = \frac{\sum_i \xi(i) \times A_i}{A} \tag{12.12}$$

Fig. 12.8 Total pressure rake probe
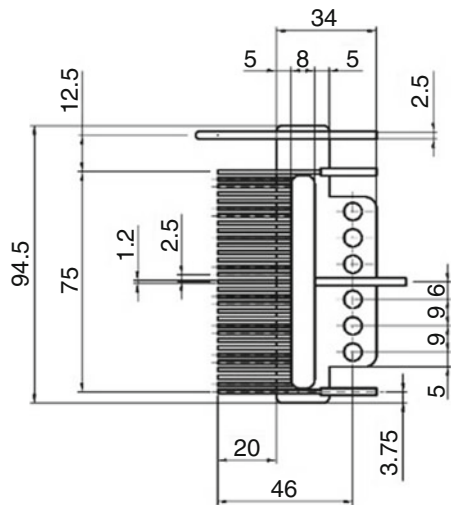
It is important to consider that the efficiency of the flow control is in relation to the power input P_{in} of the synthetic jet generator (with flow control power supply devices). Efficiency of active flow control (synthetic jet) can be derived by the efficiency of the synthetic jet η_{sj}. The specific work loss w_{loss} is calculated from the total loss coefficient and main flow velocity.

$$w_{loss} = \xi_{tot} \times \frac{1}{2} \times U_\infty^2 \tag{12.13}$$

The specific saved-up work w_s is derived from the difference of the total loss coefficients with and without the influence of the synthetic jet.

$$w_s = [\xi_{tot}(0) - \xi_{tot}(f)] \times \frac{1}{2} \times U_\infty^2 \tag{12.14}$$

Specific added work in the channel is derived as

$$w_{add} = \frac{P_{in}}{\dot{m}_{chan}} \tag{12.15}$$

where P_{in} is electric input power and m_{chan} is mass flow rate in the channel. The efficiency of the synthetic jet η_{sj} is defined by the ratio of difference between the specific saved-up work and the added work to the specific added work. The efficiency of the synthetic jet expresses how much energy is saved in relation to the added energy. Value of efficiency of the synthetic jet can be negative.

$$\eta_{sj} = \frac{w_s - w_{add}}{w_{add}} \tag{12.16}$$

12.5   Conclusions

The development in the area of the boundary layer control brings broad possibilities in application of synthetic jet in practice. Synthetic jet application opens new options on how to design machine aerodynamics.

This chapter presented the concept of applying synthetic jets for boundary layer control. Dependencies between natural vortex shedding frequency, exciting frequency f of the synthetic jet, intensity (momentum coefficient c_μ) of the synthetic jet, and design of the synthetic jet generator were mentioned. Finally, the process of designing a synthetic jet generator using LEM was outlined.

References

Babinsky H, Ogawa H (2008) SBLI control for wings and inlets. Shock Waves 18:89–96

Brouckova Z, Safarik P, Travnicek Z (2011) Region of parameters of synthetic jets. STČ, FME, CTU in Prague, Proceedings of Students Work in the Year 2010/2011, s. 23–38

Chen Y, Liang S, Aung K, Glezer A, Lagoda J (1999) Enhanced mixing in a simulated combustor using synthetic jet actuators. AIAA Paper 99–0449

Dandois J, Garnier E, Sagaut P (2007) Numerical simulation of active separation control by a synthetic jet. J Fluid Mech 574:25–58

Doerffer P, Hirsch C, Dussauge JP, Babinsky H, Barakos GN (2010) Unsteady effects of shock wave induced separation. Notes on numerical fluid mechanics and multidisciplinary design—UFAST, vol 114. Instytut Maszyn Przepływowych PAN, Gdańsk

Gallas Q, Mathew J, Kaysap A, Holman R, Nishida T, Carroll B, Sheplak M, Cattafesta L (2002) Lumped element modeling of piezoelectric-driven synthetic jet actuators. AIAA J 2002–0125

Gallas Q, Wang G, Papila M, Sheplak M, Cattafesta L (2003) Optimization of synthetic jet actuators. AIAA J 2003–0635

Greenblatt D, Paschal BK, Yao C, Harris J (2005) A separation control CFD validation test case Part 2. Zero efflux oscillatory blowing. In: 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV 2005, AIAA Paper 2005–0485

Holman R, Utturkar Y, Mittal R, Smith BL, Cattafesta L (2005) Formation criterion for synthetic jets. AIAA J 43(10):2110–2116

Matejka M, Pick P, Prochazka P, Nozicka J (2009) Experimental study of influence of active methods of flow control on the flow field past cylinder. J Flow Vis Image Process 2009(4): 353–365

Matejka M, Hyhlik T, Skala V (2011) Effect of synthetic jet with amplitude modulation on the flow field of hump. In: 22nd International Symposium on Transport Phenomena. Delft, s. 31–39

Morse MP, Ingard KU (1968) Theoretical acoustics. Osborne-McGraw-Hill, USA

Nae C (2000) Unsteady flow control using synthetic jet actuator. AIAA J, AIAA 2000–2403

Seifert A, Bachart T, Koss D, Shepshelovich M, Wygnanski I (1993) Oscillatory blowing: a tool to delay boundary layer separation. AIAA J 31:2052–2060

Smith BL, Glezer A (2002) Jet vectoring using synthetic jets. J Fluid Mech 458:21–54

Timchenko V, Reizes J, Leonardi E, de Vahl Davis G (2004) A criterion for the formation of micro synthetic jets. In: ASME International Mechanical Engineering Congress and Exposition, Anaheim, s. 197–203

Trávníček Z, Broučková Z, Kordík J (2012) Formation criterion for synthetic jets at high Stokes numbers. AIAA J 50(9):2012–2017