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FLOW CONTROL – PRELIMINARY DESIGN OF SYNTHETIC JET GENERATOR

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Abstract
The aim of this paper is to summarize application of synthetic jet generator for flow control. Defining of corresponding frequency of the synthetic jet, which should agrees to the natural vortex shedding frequency, is mentioned. Influence of non-dimensional characteristic as Strouhal number, Stokes number and Reynolds number of output orifice of synthetic jet generator to the intensity of synthetic jet is discussed. Preliminary design of the synthetic jet generator using Lumped Element Method (LEM) is described.

Key words: flow control; active flow control; sythetic jet; design; amplitude modulation, LEM

INTRODUCTION

Synthetic jet - alternating blowing and suction is a well-known shear layer active flow control technique. By means of the synthetic jet is possible to lower drag, to increase lift or to intensify heat transfer in 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 and Smith & 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. 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 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. 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.

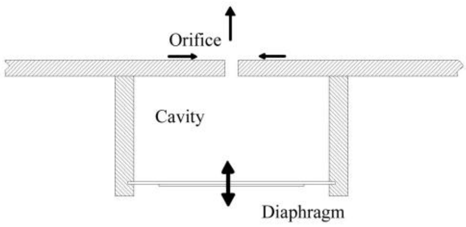

Fig. 1: The synthetic jet generator - schema

FREQUENCY OF THE SYNTHETIC JET AND CRITERIA OF ITS EXISTANCE

The efficiency of the flow control under influence of the synthetic jet strongly depends particularly on two variables. First variable is the exciting frequency of the synthetic jet f, which should corresponds 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^+.

$$F^+ = \frac{f \cdot X_{te}}{U_\infty} \tag{1}$$

Optional value of nondimensional frequency F^+ can be set at value of 1.2, Greenblat at 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.

$$c_\mu = \frac{\rho_o \cdot u_o'^2 \cdot h}{1/2 \cdot \rho_\infty \cdot U_\infty^2 \cdot l} \tag{2}$$

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

$$u_o' = \frac{\sqrt{\int_0^h \bar{u}_o(y)^2 dy}}{h} \tag{3}$$

and time mean velocity (positive part of period T):

$$\bar{u}_o = \frac{2}{T} \cdot \int_0^{\frac{T}{2}} u_o(t) \cdot dt = \dots = \frac{1}{T} U_{\max} \int_0^{T/2} \sin(\omega t_s) dt_s = \frac{U_{\max}}{\pi} \tag{4}$$

From the equation (1) can be express frequency f of the synthetic jet. Value of X_{te} is the distance from output orifice of the synthetic jet position to the point of reattachment – mixing length. High 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. Now, size of output orifice h from the equation (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, Greenblat at al., 2005, Smith & Glezer, 2002. Then minimal value of momentum coefficient c_μ corresponding to this optimal value of nondimensional frequency F^+ is about 0.2%, Greenblat at al., 2005.

The last important point is to check, if the synthetic jet fulfill above mentioned criteria of existence of the synthetic jet, Brouckova et al., 2011, 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 (5), Reynolds number of output orifice of the synthetic jet generator Re_o (6) and Stokes number of output orifice of the synthetic jet generator St_o (7).

$$Sh_o = \frac{f \cdot D}{u_o} = \frac{D}{T \cdot u_o} = \frac{D}{L_O} = \frac{2 \cdot f \cdot D}{\overline{U}} = \frac{Sh_H}{\pi} \tag{5}$$

$$\mathrm{Re}_o = \frac{u_o \cdot D}{\nu} = \frac{\mathrm{Re}_H}{2} = \frac{\mathrm{Re}_{\max}}{\pi} = \frac{\mathrm{Re}_L}{L_O} \cdot D \tag{6}$$

$$St_H = \sqrt{Sh_H \cdot \mathrm{Re}_H} \tag{7}$$

Fig. 2 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. Stokes number should be lower than about 10.

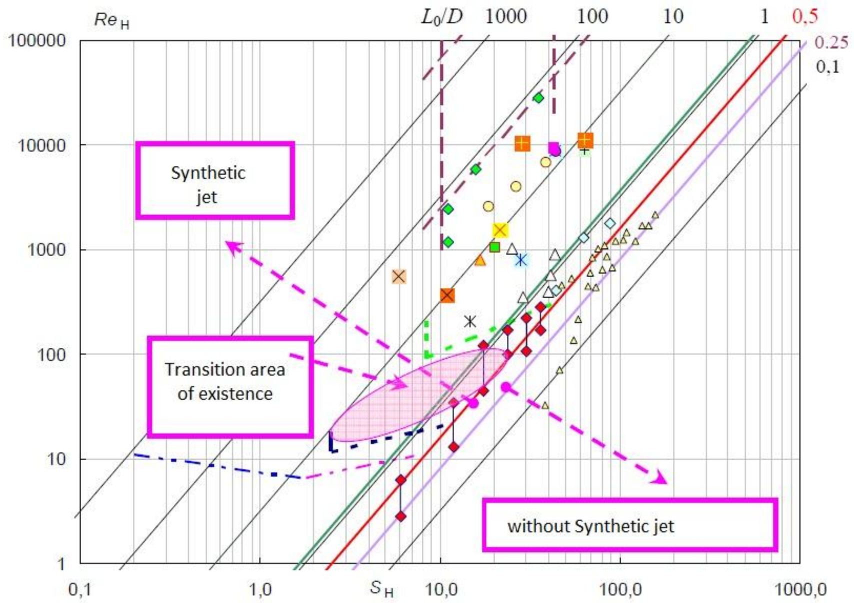

Fig. 2: Criteria of existence of the synthetic jet, Brouckova et al 2011

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. 1 represents the synthetic jet generator converted to electrical circuit, see Fig. 3.

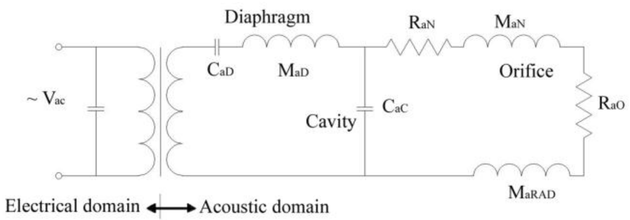

Fig. 3: Lumped Element Mode - equivalent electrical circuit

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 electro-acoustic 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 above mentioned values. Impedance Z, expressed from those values, is used to calculate volume flow rate in output orifice, (8) and (9).

$$\frac{U_V}{Z} = \frac{\dot{V}}{\phi} \tag{8}$$

$$da = \frac{\phi}{C_{aD}} = \frac{\Delta V}{U_V} \tag{9}$$

where U_v is applied voltage, V total flow rate and ϕ is electroacoustic turns ratio. 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, (9), are function of s = ω.j, where ω = 2.π.f. Thereafter the related equation is:

$$\frac{\dot{V}_{orifice}(s)}{U_V(s)} = \frac{da(s)}{a_4 \cdot s^4 + a_3 \cdot s^3 + a_2 \cdot s^2 + a_1 \cdot s + 1} \tag{10}$$

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. 4. 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.

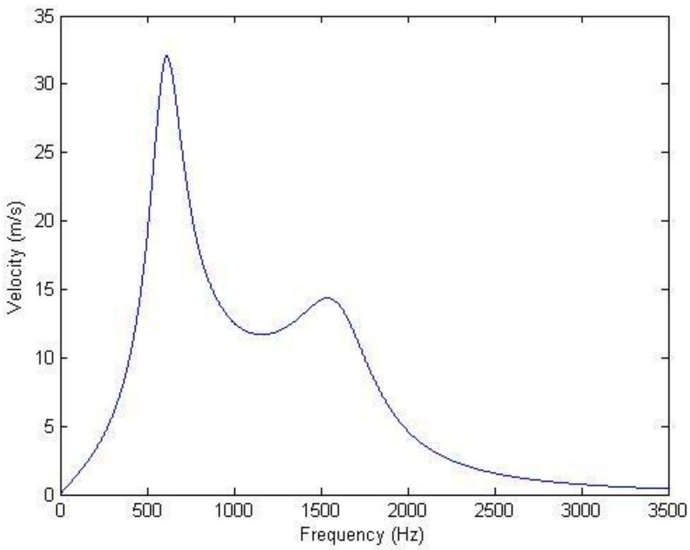

Fig. 4: Amplitude – frequency characteristic, dependence of velocity to exciting frequency

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 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.

CONCLUSIONS

Flow control technique using synthetic jet was summarized. Corresponding frequency of the synthetic jet must be used to obtain positive influence to the flow field. Procedure for the synthetic jet generator design using LEM was introduced. Mutual dependency 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 was mentioned.

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