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Non-harmonic excitation of synthetic jet actuators based on electrodynamic transducers

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ABSTRACT

An axisymmetric synthetic jet actuator based on a loudspeaker was tested experimentally. The actuator was driven by a voltage waveform, whose shape was derived from a pulse-width modulated signal. With the duty cycle and frequency of the excitation voltage varied at a constant electrical input power level and fixed nozzle diameter, the momentum flux of the jet (the jet thrust) was measured using precision scales. The maximum of the measured momentum flux was found at the optimum driving frequency and the duty cycle. This experiment was repeated for several input power levels and nozzle diameters, and the resultant optimal driving configurations were compared with adequate results for a harmonically driven actuator with identical geometry. Based on a newly introduced dimensionless nozzle diameter, a criterion was found that states conditions under which it is advantageous to use the suggested non-harmonic excitation.

1. Introduction

Synthetic jets (SJs) are fluid flows that are formed downstream of a nozzle in which a pulsed flow is driven; see (Smith and Glezer, 1998; Cater and Soria, 2002). The pulsed flow excitation is usually provided by an oscillating piston or elastic diaphragm, which closes one side of a cavity that is connected with the ambiance by the nozzle. Such a device producing SJs is usually called a synthetic jet actuator (SJA).

Downstream flow continuation and formation of flow structures similar to a continuous jet (Smith and Swift, 2003) are typical properties of SJs. Many potential applications of SJs have been proposed since the end of the 20th century. The promising applications of SJs have been found especially in boundary-layer separation control (Rathnasingham and Breuer, 2003; Hong, 2006), jet vectoring (Ben Chiekh et al., 2012; Smith and Glezer, 2002), heat transfer enhancement (Trávníček and Tesař, 2003; Valiorgue et al., 2009), and mixing (Xia and Zhong, 2012; Al-Atabi, 2011). A variant of the SJ, namely, a hybrid SJ, has been investigated more recently (Trávníček et al., 2006; Kordík and Trávníček, 2013b).

If synthetic jet actuators (SJAs) based on elastic diaphragms (e.g., based on a loudspeaker or a piezoceramic diaphragm) and input/output energy balance are considered, then the most advantageous operating conditions are found at the resonance. Therefore, many authors concentrated their efforts on location and prediction of the SJAs resonances (see, e.g., (Gallas et al., 2003; Tang and Zhong, 2009; Kordík and Trávníček, 2013a)). Operation of a SJA at the resonance frequency is a possible means to achieve the maximal exploitable outlet quantities such as the momentum flux from the actuator nozzle. Another way to increase the momentum flux can be a utilization of a non-harmonic excitation, as is proposed in this paper.

The utilization of non-harmonic excitation of a SJA is not a new idea; for example, Mossi et al. (2005) tested SJAs based on piezoceramic diaphragms. Their results showed that maximum velocity magnitude was markedly different with the different excitation waveform applied. In particular, a sine waveform produced a weaker jet in comparison with application of saw-tooth input signal.

Another study was performed by Zhang and Wang (2007), who analyzed numerically a SJA at chosen constant dimensionless stroke length and the Reynolds number. Their model had a prescribed diaphragm velocity having a shape of a sine-function with different duration times of positive and negative waveform parts. The authors introduced the suction duty cycle factor as a ratio of the suction and extrusion strokes duration times. They found that the strength of the vortex pair formed during the extrusion cycle increases with the value of the suction duty cycle factor. These results were verified experimentally later in Wang et al. (2010), and the axisymmetric case of a SJA driven by this novel signal was studied experimentally in Duan and Wang (2016). Even more recent papers (Hao et al., 2010; Feng and Wang, 2012, 2014) of the same group of authors studied effects of the novel excitation on wake vortex shedding modes, or its possibilities in

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Nomenclature

B	damping, kg/s
Bl	loudspeaker coil force factor, T·m
D	diameter, m
d	duty cycle, %
e	electrical voltage, V
E	electrical voltage amplitude, V
f	driving frequency, Hz
g	gravitational acceleration, m/s^2
i	electrical current, A
L	length, m
M	momentum flux, N
m	mass, kg
P	input power, W
R	loudspeaker coil ohmic resistance, Ω
S	surface area, m^2
T	time period, s
t	time, s
u	velocity, m/s
ξ	loss coefficient at cavity-nozzle-ambiance transition
ρ	density, kg/m^3

Subscripts

0,1,2	general indexes
d	diaphragm
e	electrical
E	extrusion stroke
h	harmonic
max	maximum
n	nozzle
o, opt	optimal
u	non-harmonic

Superscripts

*, **	dimensionless

flow control of separation in the flow over a circular cylinder.

In the abovementioned literature dealing with the non-harmonic excitation (Zhang and Wang, 2007; Wang et al., 2010; Duan and Wang, 2016; Hao et al., 2010; Feng and Wang, 2012, 2014) the diaphragm velocity is considered as the defined input. In contrast, electrical input parameters, particularly the voltage, are taken here as the input waveform, whose shape is going to be modified. Therefore, the current results are closely bound with the dynamics and the type of excitation device, which is a loudspeaker (electrodynamic transducer) here. Moreover, a different shape of the input signal was suggested, namely the input voltage waveform is chosen to be similar to a pulse-width modulated signal.

Unlike the previous literature (Zhang and Wang, 2007; Wang et al., 2010; Duan and Wang, 2016; Hao et al., 2010; Feng and Wang, 2012, 2014), where the experiments were performed at a constant Reynolds number and a dimensionless stroke length, the current concept is based on the constant electrical power input. The present experiments follow the following procedure: the duty cycle of the input voltage and the driving frequency are varied at constant power input to obtain the maxima of a time mean momentum flux. The momentum flux of a sole jet as the target maximized quantity brings another fundamental view on the topic of non-harmonically driven synthetic jets. In addition, a comparison of harmonically and non-harmonically driven synthetic jets is made here in a wider scope. This allows us to formulate a criterion, which based on SJA geometry, loudspeaker parameters, and input power level, determines which type of excitation is more advantageous.

2. Problem parameters

2.1. Input voltage waveform

The present SJA is excited by a voltage waveform, which is derived from a pulse-width modulated signal (for the description of hardware arrangement producing the waveform see Section 3.1 and Fig. 2b,c). The waveform used in the current experiments is shown in Fig. 1. The waveform has a shape of two modified ellipses:

$$e = \begin{cases} E_1 \sqrt[n]{1 - \frac{(2\,|t - T_1/2|)^n}{T_1^n}}, & \text{if } 0 < t < T_1 \\ -E_2 \sqrt[n]{1 - \frac{(2\,|t - T_1 - T_2/2|)^n}{T_2^n}}, & \text{if } T_1 < t < T_2 \end{cases} \tag{1}$$

where t is time, e is the input voltage, E_1 and E_2 are amplitudes of positive and negative parts of voltage waveform (see Fig. 1) and T_1 and T_2 are their duration times, respectively. The exponent n in both Eq. (1) was chosen to be equal to 4, and Fig. 1 shows a real graph plotted using this value. The duty cycle, d is for the waveform from Fig. 1 defined as follows:

$$d = \frac{T_1}{T_1 + T_2} = \frac{T_1}{T}, \tag{2}$$

where $T = T_1 + T_2$ is the waveform period. Both waveform parts given by Eq. (1) are formed so that the surfaces S_1 and S_2, assigned in Fig. 1, are equal. This condition yields the following relation between their amplitudes E_1 and E_2:

$$E_2 = E_1 \frac{T_1}{T_2} = \frac{E_1}{\frac{1}{d} - 1}. \tag{3}$$

The amplitude E_1 was chosen so that the overall electric power input fed into the actuator corresponded to a chosen constant value. The power input P_e was evaluated as follows:

$$P_e = \frac{1}{T} \int_0^T e(t)\, i(t)\, dt, \tag{4}$$

where $i(t)$ is the input current waveform.

The designed voltage waveform has two free parameters: the driving frequency, f, (i.e. the period T) and the duty cycle, d. These

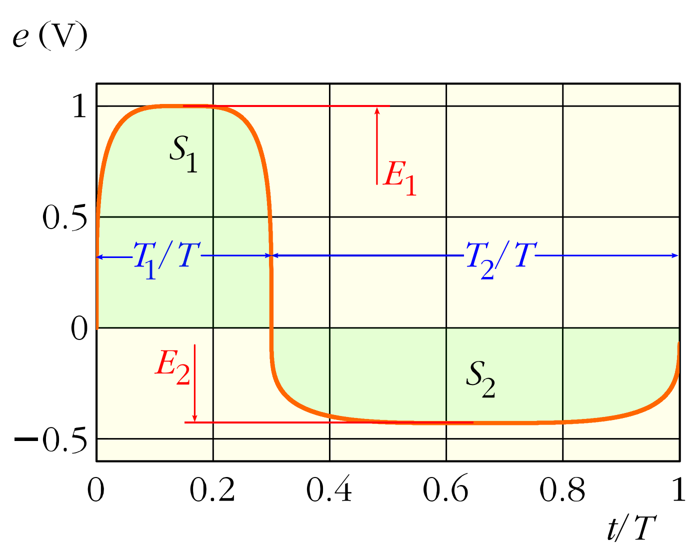

Fig. 1. The suggested input voltage waveform, an example for $E_1 = 1$, $d = 0.3$.