INFLUENCE OF MEMBRANE AMPLITUDE AND FORCING FREQUENCY ON SYNTHETIC JET VELOCITY

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Abstract: This paper presents the results of numerical investigations of a synthetic jet actuator for an active flow control system. The Moving-Deforming-Mesh method as a boundary condition is used to capture the real physical phenomenon. This approach allows precise investigation of the influence of the membrane amplitude, the forcing frequency and cavity effect on the jet velocity. A synthetic jet actuator is simulated using a membrane perpendicular to the surface arrangement. Two cases are investigated to maximize the jet velocity – an actuator with one and two membranes in a cavity. Two main forcing frequencies can be specified in the synthetic jet actuator application. One corresponds to the diaphragm natural frequency and the other corresponds to the cavity resonant frequency (the Helmholtz frequency). This study presents the results of actuators operating at the two abovementioned forcing frequencies. The simulation results show an increase in the jet velocity as a result of an increase in the membrane peak-to-peak displacement. This study was a preliminary study of the synthetic jet actuator for single and double membrane systems. The optimization process of the synthetic jet actuator geometry and parameters is ongoing. Numerical results obtained in these investigations are to be validated in the experimental campaign.

Keywords: synthetic jet, active flow control, flow separation

1. Introduction

Aerodynamic properties have been widely enhanced with the use of flow control devices in the engineering applications, *e.g.* aeroplanes, helicopters and wind turbine rotors [1, 2] for many years. Flow separation or transition point control can be done by passive methods which do not require any additional power supply (Gurney Flaps, vortex generators, aerofoil shape modification) [3, 4] or using active devices with an additional energy input (steady blowing, synthetic jet actuators) [5].

In fluid dynamics a synthetic jet flow is a jet flow synthesized from an ambient fluid where the stream of the fluid mixes with the surrounding medium.

This can be generated using an electromagnetic, piezoelectric or mechanical driver. The synthetic jet fluid motion is obtained by an alternate suction and ejection of fluid through an orifice or a slot bounding a small cavity. This is generated by a time periodic oscillation of a diaphragm built into the cavity wall. Oscillation of the membrane is a response of the piezoelectric material to the applied voltage. During the oscillation cycle the cavity volume alternately decreases the expelling fluid during the blowing cycle and increases the cavity volume drawing-in fluid during the suction cycle. Membrane can be perpendicular or parallel to the surface in which a hole or a slot are introduced.

This paper presents the results of a numerical investigation of a synthetic jet actuator (Figure 1) with one and two membranes perpendicular to the surface.

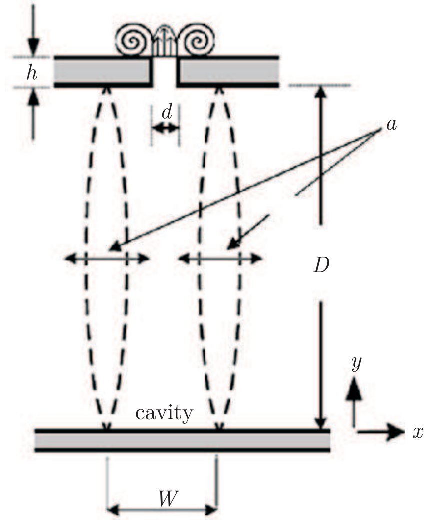

Figure 1. Synthetic jet actuator scheme

Many studies of the synthetic jet have been performed using simplified actuator models:

- the boundary condition at the orifice exit (the wall normal velocity profile) [6, 7];
- the moving piston condition [8].

The authors of this paper present the results of the moving deforming mesh method for the synthetic jet simulation. The numerical modeling of the synthetic jet actuator is described in the following sections. Different forcing frequencies and conclusions are presented based on the results of the parametric investigations for various membrane amplitudes.

2. Numerical modeling

This section describes the numerical simulation details. The Computational Fluid Dynamic (CFD) software, the turbulence model used in the simulation and other simulation parameters are described. The Moving-Deforming-Mesh method used for the two-dimensional CFD vibrating diaphragm simulation is presented in this section, as well.

The commercial ANSYS Fluent package is used for 2D CFD simulations and Gambit is used for the geometry definition and grid creation. Equations of conservation of mass and momentum for two-dimensional geometry are solved during the compressible flow simulation. Compressibility effects have to be taken into account because of the change of the density as a result of the moving diaphragm.

One can distinguish two major sections of the proposed geometry. The first region is the ambient air outside the actuator where the jet is developed and the second region includes a synthetic jet actuator cavity. Ambient air and the cavity are connected through a duct. The ambient air boundary conditions are specified as a pressure outlet while all the surfaces are considered as walls.

The ambient air region is meshed with structured mesh, as well as the duct and central part of the synthetic jet actuator cavity. In the cavity regions adjacent to the moving walls a tri-pave unstructured mesh has to be used to allow displacement of membrane nodes during the simulation. Unstructured mesh in the deforming zone is a requirement of the Moving-Deforming-Mesh feature in the software (described later). This approach allows reducing the number of re-meshing nodes during every time step. The combination of the structured and unstructured mesh significantly reduces the size of the model and reduces the needed computational power and simulation time as a result.

The Shear Stress Transport k-ω (SST) turbulence model [9] is a two-equation eddy-viscosity model which has been proven to be very effective in similar applications. The use of a k-ω formulation in the inner parts of the boundary layer makes the model directly usable all the way down to the wall through the viscous sub-layer, hence, the SST k-ω model can be used as a Low-Re turbulence model without any extra damping functions. The SST formulation also switches to a k-ε behavior in the free-stream.

By default, ANSYS FLUENT updates the node positions on a dynamic zone by applying the solid-body motion equation. This implies that there is no relative motion between the nodes on the dynamic zone. However, if there is a need to control the motion of each node independently, the User Defined Function DEFINE_GRID_MOTION can be used. A mesh motion UDF can, for example, update the position of each node based on the deflection due to the fluid-structure interaction. The improved synthetic jet actuator model with Moving-Deforming-Mesh (MDM) allows replacing the surface boundary condition with the deforming wall. The membrane deformation profile from '1z' Finite Element model can be imported as an input to the CFD simulation. MDM makes it possible to simulate the flow in the cavity and capture the real physical phenomenon.

Membrane deformation profile for 2D model is written in Formula (1) as:

$$x = a\sin(2\pi f\cdot t)\cdot\left(1-\left(\frac{y}{r}\right)^2\right)^2 \tag{1}$$

Where: x is the membrane displacement in x-direction (m); a is the displacement amplitude (m); f is the forcing frequency (Hz); t is the time (s); y is the y-axis coordinate; r is the membrane radius (m).

A lot of studies of the synthetic jet have been performed using a simplified model of the actuator. One of the methods is based on the boundary condition at the orifice exit (the wall normal velocity profile). Another method of representing the synthetic jet behavior is a moving piston condition. One has to notice that it is only the moving deforming membrane boundary condition that provides the most accurate physical phenomenon. On the other hand, the use of the re-meshing method for every time step requires a lot of computational power and is time consuming.

3. Parametric study

There is a need to study the effect of synthetic jet individual parameters for synthetic jet flow maximization. A parametric study was carried out to find the optimal parameters. Numerical simulations of the actuator for various membrane amplitudes and different forcing frequencies were conducted. All the simulations were performed for two cases – for one membrane in a cavity and for two membranes in a cavity (Figure 1).

The influence of the vibrating membrane amplitude on the jet velocity was investigated varying the peak-to-peak displacement of the diaphragm from $a = 2 \cdot 10^{-5}$ m to $a = 1 \cdot 10^{-4}$ m. As the displacement amplitude increased the change of the cavity volume increased during the cycle as well. As a result, more fluid was forced to exit the actuator during the blowing phase. It was decided to undertake a numerical simulation of an oscillating membrane in a wide range of displacement values to maximize the jet velocity. One has to keep in mind the fact that piezoelectric membrane displacement is a function of the applied voltage, therefore, the power consumption during the actuator operation can be an issue.

At resonant frequencies, the synthetic jet generator can generate maximum output velocity. The synthetic jet generator should be operated on its resonant frequencies to reduce the power input of energy. A preliminary design of the synthetic jet generator can be made using the Lumped Element Modeling (LEM) [10] method based on the electroacoustic theory. The LEM method is based on an analogy between electrical and acoustic domains. Two main forcing frequencies can be specified in the synthetic jet actuator application. One corresponds to the diaphragm natural frequency and the other corresponds to the cavity resonant frequency (Helmholtz frequency).

Membrane structural resonance

The diaphragm natural frequency (f_{mem}) depends on the material properties, mass, dimensions of diaphragm. Using the LEM method the diaphragm natural frequency is given by the expression:

$$f_{\mathrm{mem}} = \frac{1}{2\pi}\sqrt{\frac{1}{M_{aD} \cdot C_{aD}}} \tag{2}$$

Where: M_{aD} is the diaphragm acoustic mass; C_{aD} is the acoustic compliance of a homogeneous clamped circular plate. From the diameter of an oscillating circular membrane in the LEM simulation, the deformation profile is exported and used as the input in the two-dimensional CFD simulations using the MDM method. Based on the LEM method the membrane natural frequency used in the simulations is 740 Hz.

Helmholtz frequency

Thinking of the cavity resonance in terms of an oscillating mass of air can give some insight about how the physical properties of the cavity affect the resonant frequency. This can be visualized by the process of pushing extra air into the cavity where overpressure is produced. If the opening to the cavity is larger, the excess air can escape more rapidly to bring the pressure down to external conditions. This leads to a higher cavity resonant frequency. If the neck of the cavity is longer, there is more resistance to the flow of the excess air and the resonant frequency is lowered. If the cavity volume is increased, then, it takes a greater excess mass of air to produce a given overpressure, and it therefore takes longer for that excess pressure to bring it down to external conditions. The larger cavity will have lower resonant frequency. In general the cavity resonant frequency is given by the expression:

$$f_{\mathrm{cav}} = \frac{c}{2\pi}\sqrt{\frac{A}{V \cdot L}} \tag{3}$$

Where: c is the sound speed (m/s); A is the area of opening (m^2); V is the cavity volume (m^3); L is the opening length (m).

The synthetic jet actuator model parameters used in the presented study are given in Table 1.

Table 1. Synthetic jet actuator model parameters

peak-to-peak displacement a (mm)	membrane diameter D (mm)	orifice diameter d (mm)	duct length h (mm)	chamber width W (mm)		number of membranes		forcing frequency f (Hz)	
0.02									
0.04									
0.06	25	1.0	1.0	1.5	2.0	1	2	740	1650
0.08									
0.10									

This paper presents the results for the actuator Helmholtz frequency of 1650 Hz

4. Results

Simulations were performed for an actuator with one membrane and two membranes in the cavity. The results of the influence of the vibrating membrane amplitude on the jet velocity for one membrane in the cavity are presented in

Figure 2. Lines represent velocity magnitude V_{mag} and velocity y-component V_y (in the jet direction) for the membrane resonant frequency of 740 Hz and the cavity resonant frequency of 1650 Hz. All the velocity values are the maximum values for the jet during a blowing cycle. The velocity magnitude and velocity y-component are calculated on the actuator exit orifice diameter. The results of the influence of the vibrating membrane amplitude on the jet velocity for two membranes in the cavity are presented in Figure 3. The membranes are actuated in the opposite

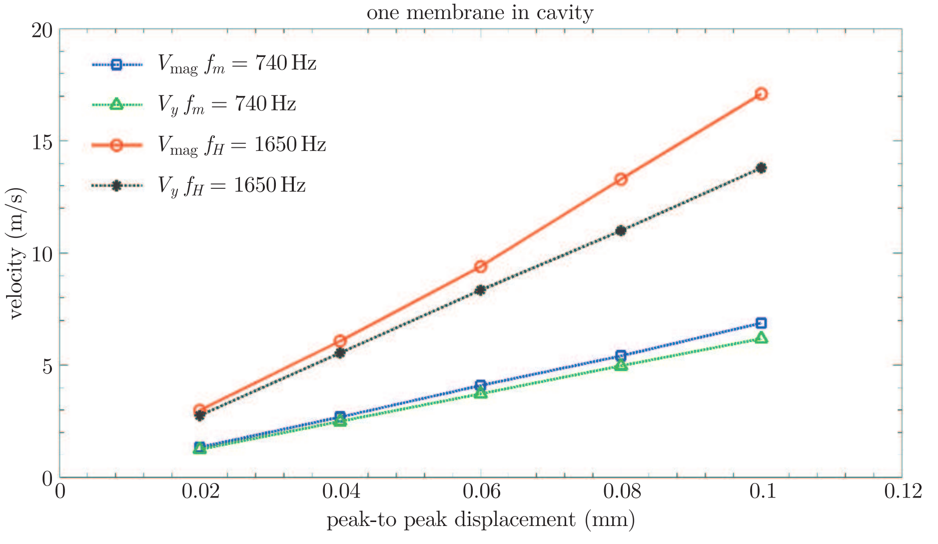

Figure 2. Jet velocity for one membrane in cavity (membrane resonant frequency $f_m = 740$ Hz, cavity resonant frequency $f_H = 1650$ Hz)

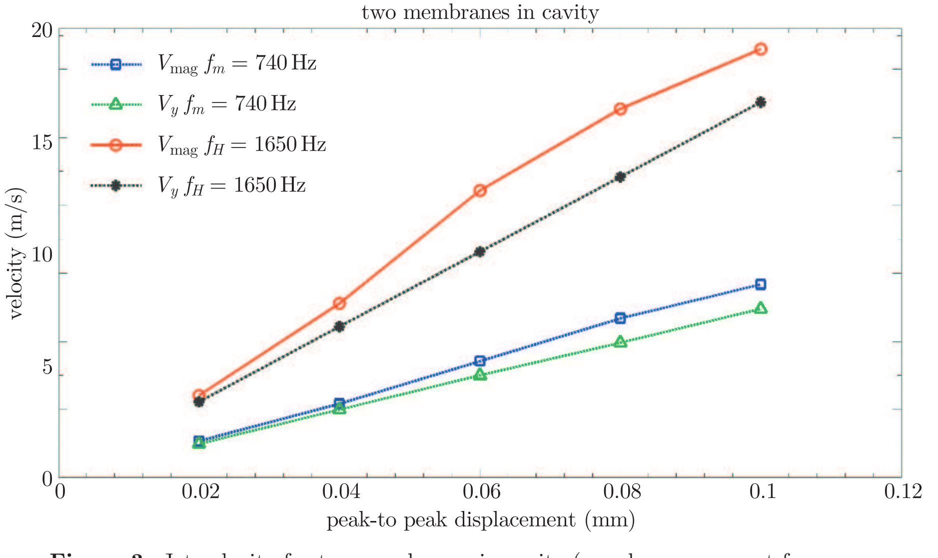

Figure 3. Jet velocity for two membranes in cavity (membrane resonant frequency $f_m = 740$ Hz, cavity resonant frequency $f_H = 1650$ Hz)

phase whereby the cavity volume is modified twice as much as in the previous case. As can be observed, an increase in the membrane displacement results in an approximately linear increase in the jet velocity. The higher the membrane amplitude, the higher the jet velocity that can be obtained from the actuator.

Maximum jet velocities were obtained for membrane displacement $a = 1 \cdot 10^{-4}$ m. The maximum jet velocity for one membrane in the cavity was $V = 6.88$ m/s for $f_m = 740$ Hz. The maximum jet velocity for two membranes in the cavity was $V = 14.2$ m/s for $f_m = 740$ Hz. For the cavity resonant frequency $f_H = 1650$ Hz the maximum jet velocity was $V = 17.1$ m/s for one membrane in the cavity. For two membranes in the cavity and $f_H = 1650$ Hz the maximum jet velocity was $V = 31.5$ m/s. The ratio of jet velocities for the actuator arrangement with two membranes to one membrane in the cavity is presented in Table 2. The use of a second membrane in the cavity gives the jet velocity two times higher for the membrane resonant frequency and for the cavity resonant frequency, as well.

Table 2. Ratio of jet velocities for actuators with two membranes to one membrane in cavity

Amplitude (m)	$f_m = 740$ Hz		$f_H = 1650$ Hz	
	V_{mag}	V_y	V_{mag}	V_y
0.00002	2.01	1.98	2.02	2.01
0.00004	2.02	2.00	2.11	2.00
0.00006	2.09	2.02	2.24	1.99
0.00008	2.16	1.99	2.04	2.01
0.0001	2.06	2.00	1.84	2.00

Flow separation in the duct affects the jet velocity at the actuator exit. This can be observed in the difference between the jet velocity magnitude and the jet y-direction velocity component presented in Figures 2–3 for one and two membranes in the cavity, respectively.

Contours of the velocity magnitude and vortex structure at the actuator exit in the blowing cycle for membrane peak-to-peak displacement $a = 6 \cdot 10^{-5}$ m and one membrane in the cavity are presented in Figures 4–5. Contours of the velocity magnitude and vortex structure at the actuator exit in the blowing cycle for membrane peak-to-peak displacement $a = 6 \cdot 10^{-5}$ m and two membranes in the cavity are presented in Figures 6–7. For forcing frequency $f_m = 740$ Hz and the actuator with two membranes in the cavity, the reversed flow area in the duct is much larger compared to the case with the actuator with one membrane in the cavity. This phenomenon can be observed for the forcing frequency $f_H = 1650$ Hz, as well.

5. Conclusions

This paper presents a numerical simulation of a synthetic jet actuator using the Moving-Deforming-Mesh method. The synthetic jet actuator is simulated using a membrane perpendicular to the surface arrangement. Investigations of

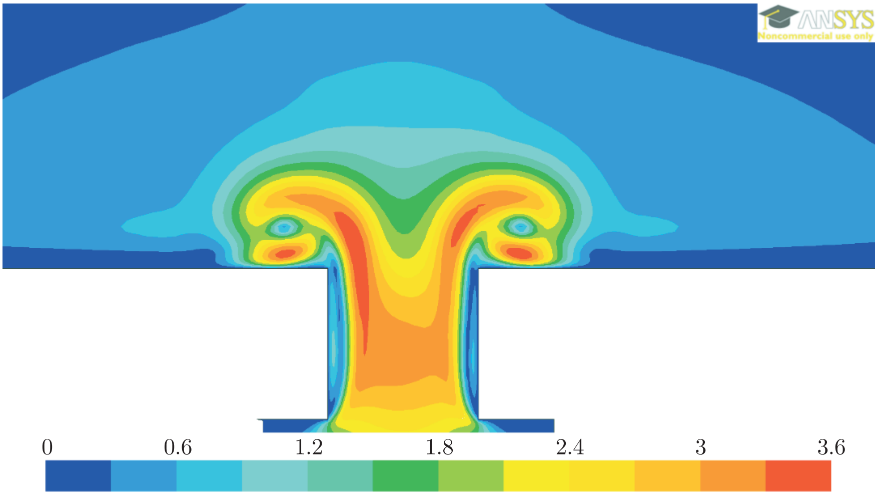

Figure 4. Contours of velocity in the blowing cycle, one membrane, $f_m = 740\,\mathrm{Hz}$

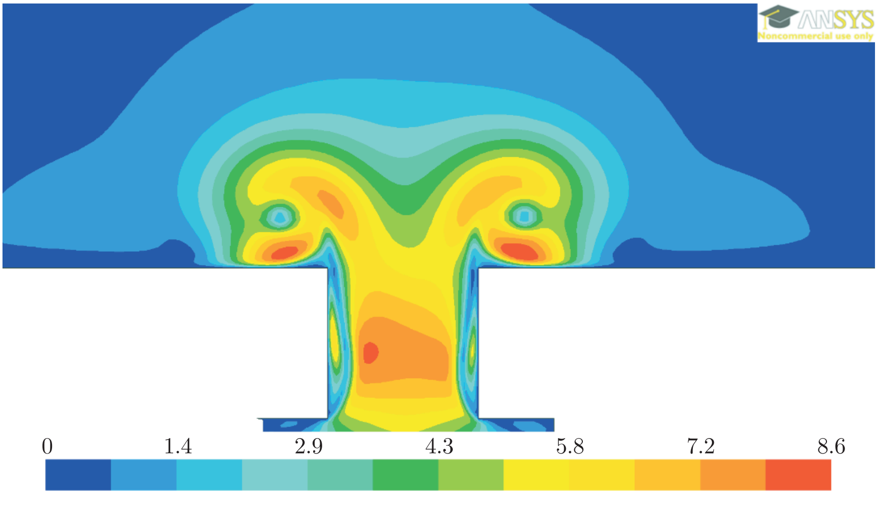

Figure 5. Contours of velocity in the blowing cycle, one membrane, $f_H = 1650\,\mathrm{Hz}$

the influence of the membrane amplitude, the forcing frequency and cavity effect on the jet velocity were carried out and the results are reported. Two forcing frequencies were used, one of which corresponded to the diaphragm natural frequency and the other which corresponded to the cavity resonant frequency (Helmholtz frequency). The simulation results show that an increase in the membrane displacement results in an approximately linear increase of the jet velocity. The higher the membrane amplitude, the higher the jet velocity that can be obtained from the actuator. The use of a second membrane in the cavity gives the jet velocity two times higher for the membrane resonant frequency and for the cavity resonant frequency, as well. Maximum jet velocities were obtained for membrane displacement $a = 1 \cdot 10^{-4}\,\mathrm{m}$. The use of a second membrane in the

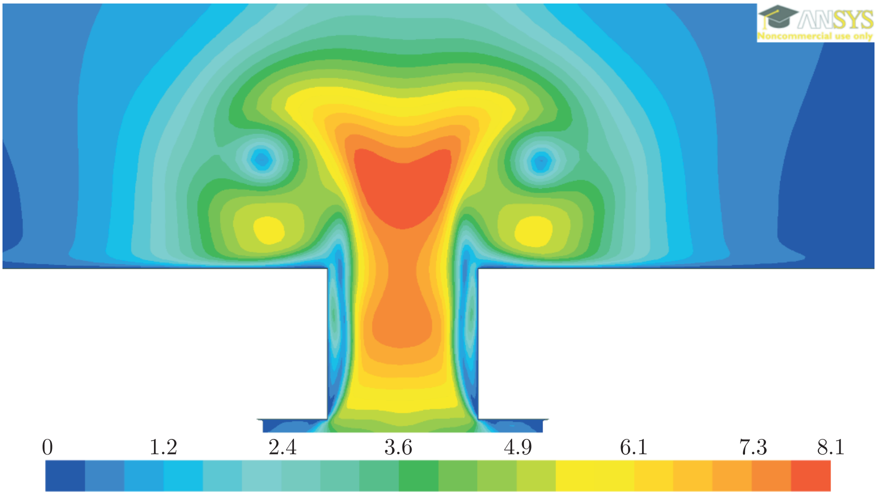

Figure 6. Contours of velocity in the blowing cycle, two membranes, $f_m = 740\,\mathrm{Hz}$

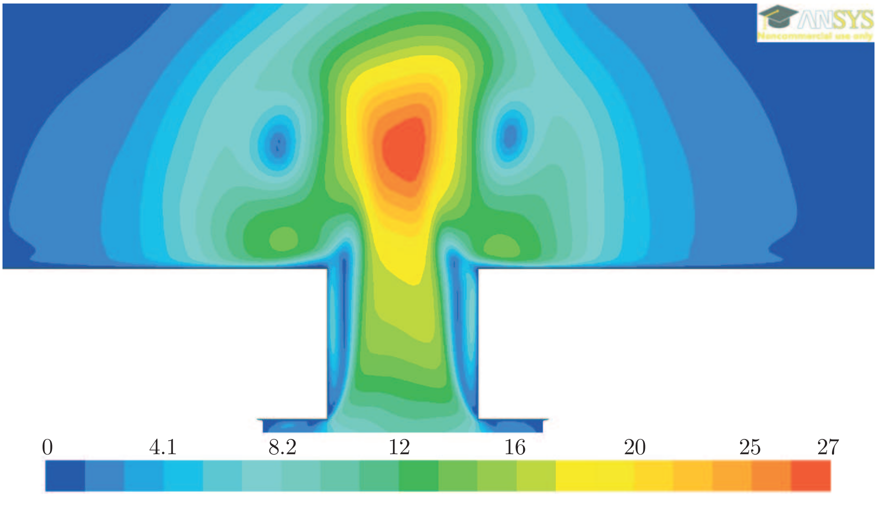

Figure 7. Contours of velocity in the blowing cycle, two membranes, $f_H = 1650\,\mathrm{Hz}$

cavity gives the jet velocity two times higher for the membrane resonant frequency and for the cavity resonant frequency as well. This study was a preliminary study of the synthetic jet actuator for active flow control. The optimization process of the synthetic jet actuator geometry and parameters is ongoing. The numerical results obtained in these investigations are to be validated in the experimental campaign.

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