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A family of CFD boundary conditions to simulate separation control

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ABSTRACT

Flow control with the aim to avoid or at least delay flow separation and thus enhance performance of rotorcraft has been a topic in various recent investigations. Increase of maximum lift combined with drag reduction in steady applications as well as improvements of lift-, drag- and pitching moment cycles in dynamic stall problems on rotor blades are of major concern.

In the present study a time accurate 2D RANS solver has been modified to enable a variety of boundary conditions for the simulation of flow control problems. With rather simple code modifications it is shown that complex control devices like synthetic jet control, running belt (wall movement) or representation of special surface materials can be taken into account in a simple and straightforward manner. Systematic calculations have shown the efficiency of the present code modifications. A common turbulence model, the Spalart/Allmaras one equation model, has been used. In addition a transition model can be taken into account as well.

The numerical calculations have been compared with corresponding experimental data where available.

1. Introduction

A considerable number of different control methodologies for flow control have been developed and investigated in recent years which may be subdivided into passive devices, i.e. [13] where vortex generators or similar surface modifications are applied to control stall. A modification of the airfoil surface by special materials may have an influence on the boundary condition such that the usual no-slip boundary condition may be changed into a virtual slip condition (see e.g. [5]). A second group is represented by dynamic devices, i.e. [2,11,7] where the leading edge part of an airfoil is drooping downward during its oscillatory period to keep the flow attached over most part of the cycle. Also within the dynamic flow control group unsteady blowing and suction with zero net mass flow has been applied. This control device is known as synthetic jet actuation. Numerical as well as experimental results of synthetic jet effects have been investigated and discussed in [14,10,9].

Moving parts of the airfoil surface i.e. by rotating cylinders have further been used to suppress dynamic stall effects completely [4]. Instead of rotating cylinders a selected portion of the airfoil upper surface may be active as a running belt or moving wall. It will be shown in the present study that most of the control devices can be simulated by simple modifications of the surface boundary condition (BC) in the present numerical RANS code [1,6]. In this code the Spalart–Allmaras One-Equation Turbulence Model [15] has been used with/without transition modeling [8].

With both static and dynamic BC-modifications most of the above mentioned control devices can be represented in the numerical code. Results and comparisons with experimental data show good correspondence with the benefit of limited computing times. The method is therefore appropriate for design purposes. Systematic variations of flow parameters, geometric details and control parameters are needed to achieve optimized conditions for separation control.

2. BC-construction

Fig. 1 shows a sketch of the modified boundary condition: Along a portion of the surface the usual no-slip boundary condition is modified by a prescribed time-dependent velocity V which is assumed here as a so-called top hat velocity distribution, i.e. the velocity along the active part of the surface is assumed as constant with respect to surface location.

As shown in Fig. 1 the velocity has a constant (steady) part and an oscillatory (sinusoidal) part respectively. The unsteady part includes the reduced frequency $\omega^* = 2\pi fc/U_\infty$ ($k = \omega^*/2$, $f =$ frequency [1/s]) of the dynamic stall oscillation. N represents the number of jet-cycles within one period of the dynamic stall cycle.

Table 1 shows control devices represented by Fig. 1. Simple static blowing and suction can be realized within the active part of the airfoil surface with the steady velocity part $V_0 > 0$ or $V_0 < 0$ respectively. The jet blowing angle α_{jet} (Fig. 1) may be varied

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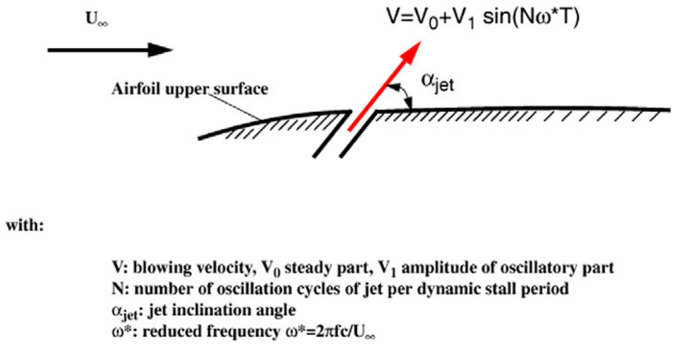

Fig. 1. Definition of boundary conditions.

Table 1
Applied BC-modifications.

Title	V_0	V_1	α_{jet}
Steady blowing	$V_0 > 0$	$V_1 = 0$	0–90°
suction	$V_0 < 0$		
Unsteady blowing/suction synthetic jet	$V_0 = 0$	$V_1 > 0$	0–90°
Moving wall running belt	$V_0 > 0$	$V_1 = 0$	0
Virtual slip	$V_0 > 0$	$V_1 = 0$	0

between 0° and 90°. The case $\alpha_{jet} = 0°$ is treating two special cases:

1) Moving wall or running belt, where a selected portion of the airfoil surface is moving with a constant static prescribed velocity V_0.
2) Virtual slip, where a part or the complete airfoil surface is covered with a special material which has the property to simulate a virtual slip condition.

With the steady part $V_0 = 0$ and the amplitude of the unsteady part $V_1 > 0$ the condition of synthetic jet is represented. The jet angle α_{jet} may vary between 0° and 90° (90° to 180° is also possible but has not been applied in the present study).

Of crucial importance for successful flow calculations with modified boundary conditions is the representation of the flow field with appropriate grids.

The present code uses a structured grid topology with 385 × 80 grid points. Fig. 2 shows the special case of a jet slot of 0.16% c (c = airfoil chord) slot width located at a selected position on the airfoils upper surface. Different options have to be fulfilled: The grid has to cover the flow details in the vicinity of the jet slot. The jet slot itself must be covered with a selected number of grid points to resolve the flow details appropriately.

To reach these goals a special redistribution routine of grid points along the airfoil surface has been developed where the position of the slot, the number of grid points across the active surface (with constant steps, see Fig. 2) as well as the usual clustering of grid points along the airfoil leading and trailing edges can be selected.

3. Synthetic jet control

In the present investigation most emphasis will be placed on the investigation of synthetic jet flow control. Fig. 3 shows a sketch of a typical synthetic jet device: Below the airfoil surface a chamber is terminated by a vibrating diaphragm. The vibrations of the diaphragm create high speed in- and outflow at the small size orifice at the airfoil surface.

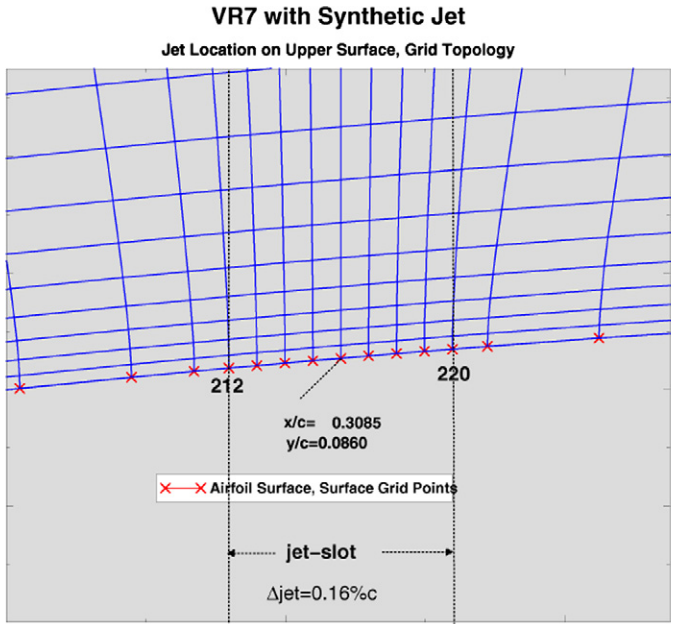

Fig. 2. Grid detail at jet slot.

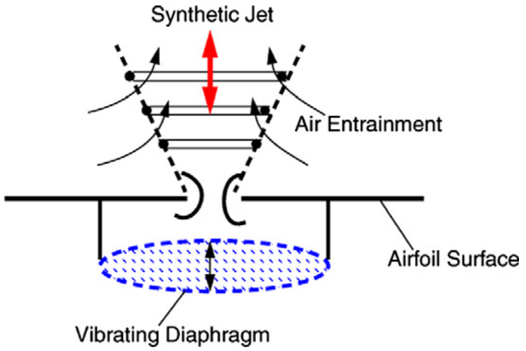

Fig. 3. Sketch of zero net mass jet actuator.

It is assumed that the amount of mass blowing out and sucked in through the slot is balanced (zero net mass). In numerical treatments of the synthetic jet problem the inner flow domain below the airfoil surface has also been taken into account in detail [12]. A considerable amount of additional numerical effort is necessary to solve the problem in this much more comprehensive manner. The present study is concentrating on the overall effect of synthetic jet control and takes the velocity distribution along the jet slot as input parameter (top hat velocity distribution).

The following discussion of synthetic jet results from the present calculations and the corresponding comparisons with experimental data [14,10] can be subdivided into two parts:

1) Influence of steady polar.
2) Dynamic stall control.

3.1. Improvement of steady polar

Fig. 4 shows calculated lift coefficients versus dimensionless time for the VR7 airfoil with as much as 80 000 time steps $\Delta T = \Delta t a_\infty / c$ (a_∞ = speed of sound, $\Delta T = 0.002$). For $M = 0.2$ the time-accurate calculations cover about 35 chord length. It is found that in all incidence cases a converged solution is reached. The present calculations have been achieved fully turbulent.