Numerical study of potential application of active suction and blowing through blade tip perforation to reduction of helicopter rotor thickness noise

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Abstract. The article explains a new concept (called here ATNC – active thickness noise control) of the application of surface transpiration to the reduction of helicopter main rotor harmonic noise. The ATNC method is based on an introduction of four cavities covered by perforated plates (connected to pressure reservoirs) at the leading and trailing edges of the outer 20% of blade span. For an exemplary, two-bladed (NACA 0012 airfoil) model helicopter rotor of Purcell in low-lifting, hover conditions (tip Mach number $M_{AT} = 0.66$ and collective $\theta = 1.5^\circ$) the results of numerical simulations, based on the SPARC code (Spalart–Allmaras turbulence and Bohning–Doerffer transpiration models), prove that the acoustic pressure fluctuations are significantly reduced by ATNC in the near-field of blade tip. The peak amplitude is attenuated by more than 45%, with a reduction of the Overall Sound Pressure Level $OASPL$ by 3.4 dB. It is shown also that the venting has not only a large impact on the acoustic radiation, but also on the aerodynamic performance of the rotor, expressed in terms of the torque penalty of 38%. The ATNC method proves to be a promising candidate as a mean of helicopter rotor thickness noise control, but not in the current arrangement.

1. Introduction
In the helicopter rotor tip-path plane the acoustic signal has a distinct, symmetrical shape, with a large negative pressure pulse that radiates mostly in the direction of forward flight, often dominating all other sources of rotocraft noise [1]. From the point of view of civil or military operations it is highly undesirable since the community annoyance is increased and the detection distance of an approaching aircraft is compromised. For helicopters operating with the advancing tip Mach numbers $M_{AT}$ in the 0.75 – 0.85 range (many contemporary designs) the shape of the impulse can be explained by considering only the monopole (thickness) term of the Ffowcs Williams–Hawkings solution of the inhomogeneous wave equation proposed by Lighthill (FWH analogy) for cases with arbitrary motion of the source surfaces (e.g. helicopter rotor blades) [2]:

$$p'(x, y, z, t) = \frac{1}{4\pi} \frac{\partial}{\partial t} \int_S \left[ \frac{\rho_0 U_n}{r|1-Ma_r|} \right] dS . \quad (1)$$

At a fixed observer position $(x, y, z)$ the acoustic pressure value $p' = p - p_0$ [Pa] ($p$ – static pressure, $p_0$ – ambient pressure) at any given instant of time $t$ is computed as a time derivative of the sum of all acoustic sources distributed over the entire surface of the blade $S$. 

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The acoustic potential (integrand) of each source panel $dS$ is evaluated at the retarded (emission) time: $\tau = t - r/a$ ($a$ – speed of sound), and is dependent on four parameters: the density of surrounding fluid $\rho_0$, the local normal velocity of the panel due to blade motion $U_n$, the distance between the panel and the observer $r$, and finally the Mach number of the panel in the observer direction $Ma_r$. As can be seen in equation 1 the in-plane acoustic pressure signal is determined by the blade shape and kinematics only, being independent of the aerodynamics. In effect an almost symmetrical acoustic signal is predicted, as shown in figure 2.

It is obvious from equation 1 that to reduce the thickness noise it is necessary to consider all mentioned components of the monopole term. For modern helicopter rotors it is primarily achieved by changing the blade tip shape ($S$), introducing thinning and sweep, accompanied by a lower hover tip Mach number $Ma_T$ (limiting both, $U_n$ and $Ma_r$). If the rotational speed of the rotor and the blade shape are considered as given, the only choice is to influence the normal velocity component $U_n$ of the source panel $dS$. It may be achieved by active suction and blowing through perforated surfaces placed directly at the blade tip. The proposed method of ATNC is effective in damping the main source of thickness noise, but introduces an important coupling since the transpiration influences not only the acoustic radiation, but also the surrounding flow-field, modifying the magnitude of the aerodynamic forces acting on the blade.

2. Mechanism of active thickness noise control (ATNC) by surface ventilation

The presented arrangement of the ATNC method is based on the application of four cavities (connected to low or high pressure supplies) covered by perforated plates and distributed at the rotor blade tip (see figure 1). Two identical (symmetrically placed with respect to the chord line), short leading edge cavities covered by perforated plates of equal, high porosity are responsible for sucking the air in. The remaining two (also identical and symmetrically positioned), extended trailing edge cavities covered by perforated plates of equal, low porosity are responsible for blowing out. A large pressure difference between both sides of each plate induces choking of the flow in the holes. Therefore, the resulting transpiration velocity $U_t$ distribution is practically independent of the external flow conditions above the surface of the ventilated wall, and may be considered as constant. The surface coverage of the perforation is chosen based on a location of the maximum values of normal velocity $U_n$ during rotation, to counteract the main source of the thickness noise. So far, only constant suction and blowing rates have been considered, leading to a uniform noise reduction efficiency in the entire rotor plane (no directivity pattern present), meaning lack of dependence on the azimuth angle of emission. The suction and blowing transpiration streams are imbalanced with approximately 2:1 ratio.

![Figure 1. A helicopter rotor blade tip equipped with ATNC.](image-url)
From the flow point of view the leading edge suction alone improves the boundary layer state. On the contrary, the trailing edge blowing disturbs highly the velocity profile leading to a negative impact on the aerodynamic performance. In forward flight the most intensive acoustic signal is emitted from the advancing blade, in a narrow azimuth range, and with strong directivity forward and near the rotor plane. In such conditions the ATNC method would need to be activated only partially, within a narrow range of azimuth (centred at approx. 90°), having a much lower impact on the performance than in the studied hover conditions. What is important, in contrast to other means of thickness noise reduction (tip thinning and lowering of tip speed), it does not require any modification of the operating conditions nor the blade outer shape. Instead, a high drag penalty has to be paid, but the control may be easily deactivated in conditions when noise emission is not a critical issue. The economical aspects of the implementation of ATNC and technological limitations of its usage are not considered here.

3. Physical and numerical modelling

The present investigation has been carried out with a cell-centred, block-structured, parallel CFD code SPARC [3]. It solves numerically the compressible, Favre-averaged Navier–Stokes equations with several 1- and 2-equation eddy viscosity models. The turbulence field is fairly well predicted by a low-Reynolds closure of Spalart–Allmaras (SA) in reference and flow control conditions [4]. The numerical algorithm is based on a semi-discrete scheme, utilizing the finite-volume formulation for the spatial discretization (central, 2nd order) and the implicit dual time-stepping approach (supplemented by the explicit Runge-Kutta method) for the integration in time (2nd order). To damp numerical oscillations and to assure a high resolution of discontinuities the artificial dissipation model SLIP is implemented. In order to increase the convergence rate the local time-stepping, implicit residual averaging, and full-multigrid techniques are incorporated in the solver. The equations are solved in a global coordinate system where the rotation is imposed by an entire grid movement using an unsteady mode (URANS). A perforated wall boundary condition, based on the empirical, Bohning–Doerffer (BD) transpiration law [5] and designed towards the modelling of surface ventilation, has been implemented in the solver [6], validated for various internal and external flows [7] (including the shock wave–boundary layer interaction control), and applied to the helicopter rotor high-speed impulsive noise reduction [8] in the past. Moreover, the SPARC code has proven to deliver reliable aerodynamic results in hover and forward flight conditions for many rotor flows. In terms of the acoustic analysis only near-field observer locations are considered. Inherent dissipation and dispersion errors, introduced by the CFD algorithm, are therefore minimised, allowing for comparison of pressure signals extracted for the reference and flow control configurations.

4. Numerical simulation of ATNC method

The initial, testing phase of the active thickness noise control (ATNC) method was performed with a two-bladed model of the UH-1H helicopter main rotor, investigated by Purcell in low-thrust hover conditions [9]. The blades were untwisted, rectangular, and had the NACA 0012 section (aspect ratio of 13.71). The tip Mach number of $Ma_T = 0.66$ and the tip Reynolds number of $Re_T = 1.6 \cdot 10^6$ (collective angle $\theta = 1.5^\circ$) were used, in-line with the experimental study of a similar rotor system conducted by Sargent and Schmitz at the University of Maryland (2012) [10]. This investigation was focused on the development of a new, on-blade acoustic cancellation method, based on the active tip jet blowing control of in-plane rotor harmonic noise. The details of the computational model (i.e. mesh topology, boundary conditions, convergence criteria, grid and time step dependency studies) are similar to the description specified in [8] for the hovering Caradonna–Tung rotor, and for this reason are omitted here. The presented URANS simulations were performed using a coarser mesh, but still consisting of an adequate $3.0 \cdot 10^6$ of control volumes per blade (in comparison with $7.0 \cdot 10^6$)
thanks to a lack of shock waves and flow separation in the investigated subsonic conditions.

The reference blade was equipped with two suction systems at the leading (0 < x/c < 0.1, c – chord length) and two blowing systems at the trailing edge (0.65 < x/c < 1.0), covering the outer 20% of blade span. The forward cavities were closed by perforated plates of high porosity of 30%. On the contrary, the rearward cavities were covered by perforated plates of low porosity of 5%. These values lay within the range of applicability of the BD model which, apart from the transpiration flow characteristics, delivers the maximum mass flow rate achievable in chocked conditions. The pressure in the connected supply system was kept at a sufficiently low (or high) level to reach the sonic velocity in the holes. This way the resulting transpiration (normal) velocity $U_t$ was independent of the local conditions near the blade surface, exhibiting constant rates of suction (60 m s$^{-1}$) and blowing (10 m s$^{-1}$). Taking into account the surface area subjected to bleeding the final mass flow rate of suction was 2.4 times larger than for blowing.

Near-field (at 1.5c from the tip) acoustic pressure fluctuations $p'/p_0$ ($p_0$ – ambient pressure) in time $t/T$ ($T$ – period of rotation), recorded in the rotor plane, at 1.11 R ($R$ – rotor radius), are depicted in figure 2 for three investigated configurations. The reference signal (ATNC off) exhibits a typical, almost symmetrical shape of the thickness noise pulse measured in wind tunnels at similar operating conditions. When the air is sucked-in through two leading edge perforated plates (ATNC on, suction only) the peak negative pressure is reduced by 25%, while the Overall Sound Pressure Level $OASPL$ is limited by 1.4 dB. In these almost non-lifting conditions the penalty is mainly considered in terms of an increase of the rotor shaft torque which is rather small and equal to 4%. Addition of blowing-out through two trailing edge perforated plates (ATNC on, suction/blowing) significantly improves the peak amplitude attenuation to 46%, leading to a drop of $OASPL$ by 3.4 dB. It is well known that the blowing has a detrimental effect on the aerodynamic performance, that’s why an increase of torque as high as 38% is observed which is considered as a price of the activation of the noise cancellation device.

![Figure 2. Impact of the ATNC method on the near-field acoustic pressure variation $p'/p_0$ in time $t/T$ at an in-plane location of 1.11 R.](image)
The Overall Sound Pressure Level $OASPL$ acoustic parameter is defined by a relation:

$$OASPL \, dB = 20 \log \frac{p'_{\text{rms}}}{p'_{\text{ref}}} \, dB, \quad p'_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} p'^2_i}$$

(2)

where $p'_{\text{rms}}$ is the root mean square of pressure fluctuations $p'$, $p'_{\text{ref}}$ is the threshold of human hearing (20 $\mu$Pa), and $N$ is the number of samples (here 1440 per period of rotation $T$). It must be stressed out that 3 dB in $OASPL$ corresponds to a reduction of $p'_{\text{rms}}$ by 50% that is directly perceived by a human ear as a two times lower noise level. The blowing induces a strong disturbance to the boundary layer, but it does not lead to flow separation for the investigated case. In forward flight the advancing blade emits the most intensive acoustic pulse when it is approaching 90° of azimuth and the maximum inflow Mach number is present (the advancing tip Mach number $Ma_{AT}$). Close to this position the angle of attack at the tip is close to 0° (for twisted blades) – a necessary requirement to balance the overproduction of lift. On the contrary, in hover (with the tip Mach number $Ma_{AT} = Ma_{AT}$) the inflow conditions are steady in time, hence the acoustic signal is of much higher amplitude. Therefore, the application of the ATNC method (in the current form) in forward flight allows for a limitation of the azimuthal coverage of the surface transpiration, which would reduce the torque penalty considerably.

5. Conclusions

The article explains the details of a new concept of the application of surface transpiration to the reduction of helicopter rotor in-plane, harmonic noise. The proposed ATNC method is based on an introduction of four cavities covered by perforated plates, through which air is sucked-in or blown-out, located at the leading and trailing edges of the outer 20% of the blade span. For the exemplary model helicopter rotor in low-lifting, hover conditions the results of numerical simulations, based on the SPARC code (SA closure and BD transpiration model), prove that the acoustic pressure fluctuations are significantly reduced by ATNC in the near-field of the blade tip. The peak amplitude of $p'$ is attenuated by 46%, with a reduction of $OASPL$ by 3.4 dB. It is shown also that the tip venting has not only a large impact on the acoustic radiation, but also on the aerodynamic performance of the rotor expressed in terms of the shaft torque penalty of 38%. The ATNC method proves to be a promising candidate as a mean of helicopter rotor thickness noise control, but not in the current arrangement.

It has been demonstrated that the proposed flow control strategy (active surface bleed) may have a radical impact on the radiated acoustic pulse amplitude and shape. The imposed transpiration velocity $U_t$ directly counteracts the normal velocity $U_n$ of the blade surface element due to rotation that is a main source of the thickness noise. Still, many questions remain unanswered, and worth further investigation. Is it possible to separate the outer flow-field from the disturbance and drag introduced by the surface ventilation? What is the impact of the ATNC method on other sources of rotary noise (e.g. loading) in out-of-plane locations? At least two possibilities arise. Instead of the applied uniform transpiration velocity for each perforated plate, $U_t$ could be non-uniformly distributed along the chordwise and radial directions, adopting its intensity to the values of $U_n$ present at the surface (known a priori). It may be easily achieved by a proper choice of the distribution and diameter of the perforation holes, reflected in a spatially varying aerodynamic porosity of the plate. Moreover, the suction and blowing in an unsteady manner would give an another option for reaching an improvement of the efficiency of ATNC. It is evident from equation 1 that it is not the absolute value of the monopole integral that is responsible for the noise generation, but its time derivative. It also seems (based on the results published in [8]) that it takes some substantial time for the external flow-field to adapt to a suddenly appearing and disappearing transpiration, with the delay reaching approximately 5° – 7° in terms of the azimuthal angle. It may suggest
an application of a series of short bursts that cannot be perceived by the outer flow. It could still provide a sufficient anti-noise pulse strength that would significantly attenuate the main source of thickness noise, without a severe impact on the rotor performance. Additionally, a supplemental valve system would allow for a convenient activation and deactivation of ATNC, leaving it operational only in conditions when it is really needed from the point of view of mission requirements. Finally, the ATNC method is general (not assigned to rotorcrafts) and may be used for any rotating machinery that is known to emit strong thickness noise (e.g. propellers).

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