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NUMERICAL MODELING OF AIR-GRASS FLOW AND BPF NOISE IN LAWN MOWERS

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ABSTRACT

The noise of domestic machines including lawnmowers becomes an urgent issue. As the technology matures, designers need better tools to predict performance and efficiency of these machines across a wide range of operating conditions and find optimal ways to reduce noise. Computational fluid dynamics is an increasingly powerful tool which enables designer to better understand all features of unsteady flow in these machines and to find optimal designs providing higher energetic characteristics, better cutting quality and lower pressure pulsation, vibration and noise. Cutting quality linked with evacuation of grass is a key lawnmower characteristic. Due to this fact application of two-phase (air-grass) lawnmower flow model is inevitable in a prediction procedure. The modeling procedure comprises determination of lawnmower average aerodynamic characteristics and CFD-CAA analysis by acoustic-vortex method to predict sound power data. This method is based on splitting the equations of compressible fluid dynamics into two modes - vortex and acoustic Computational approach applied for the vortex mode flow is a “moving body”-technique: The problem is solved in the absolute frame of coordinates and computational grid changes during the blade passing. Computations can be made in 4 stages: 1) Computation of the incompressible medium with getting average values of energetic parameters; 2) Computation of the incompressible medium for definition the source function of inhomogeneous acoustic-vortex wave equation; 3) Solution of the acoustic-vortex wave equation; 4) Computation of 2-phase flow. In the 3rd stage the pressure pulsation field can be represented like a sum of acoustic and vortex oscillation. Wave equation is solved relatively to pressure oscillation using an explicit numerical procedure. Zero pulsatory pressure is an initial condition for solution of the wave equation. The local complex specific acoustic impedance is used to define boundary conditions for the acoustical part of the pressure field. Thus the numerical procedure gives pressure pulsations field and sound power data on blade passing frequencies (BPF). For the 4th stage computations effective grass particle parameters are determined with accounting the stubble effect on flow parameters and particularities of grass particle interaction with rigid surfaces. Results of a lawnmower air-grass flow (grass particle trajectories and concentration) and corresponding BPF sound power data prediction are presented as an example of modeling procedure application..

INTRODUCTION

Currently designers need modeling capabilities which enable them to predict sound power levels as well as quality cut parameters of lawnmowers [1]. This arises with the problem of two-phase flow modeling as lower noise design requirements are somehow contradictory to quality of cut. In this work the acoustic-vortex method [2] previously developed for prediction of pressure pulsations and near field noise of bladed machines with subsonic flow is implemented in line with unsteady air-grass flow analysis.

The part of this computational procedure[3, 4] is a common iterative method for non-compressible fluid flow.

GOVERNING EQUATIONS

For numerical modeling of pressure pulsations and noise the mathematical model bases on a representation of the fluctuating flow velocity field **V** as a combination of vortex and acoustic modes,

$$\mathbf{V} = \mathbf{U} + \nabla\varphi = \mathbf{U} + \mathbf{V_a} \qquad (1)$$

Where $\mathbf{U}$ - Velocity of transitional and rotational motion of an incompressible medium (vortex mode)

$\mathbf{V_a}$ - Velocity of pure deformation (the acoustic mode)

φ - Acoustic potential

This gives the acoustic-vortex wave equation in terms of enthalpy oscillation i in the isentropic flow of a compressible fluid (***a*** – mean sound velocity):

$$\frac{1}{a^2}\frac{\partial^2 i}{\partial t^2} - \Delta i = \nabla(\nabla(\tfrac{1}{2}U^2) - \mathbf{U}\times(\nabla\times\mathbf{U})) \qquad (2)$$

The mathematical model of incompressible medium flow is based on the Navier-Stokes equation

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla(\mathbf{U} \otimes \mathbf{U}) = -\frac{\nabla P}{\rho} + \frac{1}{\rho}\nabla((\mu + \mu_t)(\nabla \mathbf{U} + (\nabla \mathbf{U})^T) + \mathbf{F} \tag{3}$$

The equation and boundary condition details are presented in [2, 3, 4].

Equations of grass particle motion in the gas phase flow are the following:

$$d\mathbf{W_p}/dt = \mathbf{F_p}$$
$$d\mathbf{X_p}/dt = \mathbf{W_p} \tag{4}$$

Where $\mathbf{X_p}$ – particle position vector, $\mathbf{W_p}$ – particle velocity vector, $\mathbf{F_p}$ – force acting on the particle.

$$\mathbf{F_p} = C_d \cdot (\mathbf{W_g} - \mathbf{W_p}) \cdot |\,\mathbf{W_g} - \mathbf{W_p}\,|\, \rho_g \cdot 3/(4 \cdot D_p) + \\ + \mathbf{g} \cdot (\mathbf{1} - \rho_g / \rho_p) \tag{5}$$

Where $\mathbf{W_g}$-$\mathbf{W_p}$ – particle blow velocity; C_d – drug coefficient; D_p – particle diameter; ρ_p – particle substance density; ρ_g – gas density.

For the drug coefficient C_d in the actual range ($|\mathbf{W_g} - \mathbf{W_p}| < 100$ м/с) the following formula is used:

$$C_d = 24/\mathrm{Re}_p + 4.4/\mathrm{Re}_p^{0.5} + 0.32$$

Where Rep – Reinolds number by particle diameter:

$$\mathrm{Re}_p = \rho_g \cdot |\,\mathbf{W}_g - \mathbf{W_p}\,| \cdot D_p / \mu_g ,$$

here μ_g – gas dynamic viscosity.

In this model they neglect the particle volume and heat transfer between gas and particles. In computational tests physical characteristics of substances assumed to be constant. In momentum equation for the gas medium the volumetric force **F** accounts particles action and stubble anisotropic resistance.

REPRESENTATION OF AIR – GRASS FLOW

Particle Characteristics

In addition to general parameters like the blade rotation speed and inclination angle one needs input parameters characterizing grass phase – width, thickness and length of grass blades, stubble height, concentration of grass blades per area, grass mass density, lawnmower speed, to define boundary conditions for the grass particles.

In the 2-phase numerical model the particles are spheres. Thus one needs to represent grass particles with spheres of the same mass and giving the same aerodynamic drag force. This is made by taking into account actual dimensions of grass particle and its flying characteristics. This enables to determine the effective diameter and density of grass particles.

Accounting grass blades dimensions, lawn mower motion speed and its design cut characteristics enables to define the mass flow rate of particles entering the flow. This particle mass flow rate put a boundary condition on the blade cut surface. Activation of the boundary condition depends on the angular position of blades as the cut plane has an inclination in relation to the ground surface. Each cut grass blade is modeled by a grass particle in the unsteady flow giving an actual representation of the grass motion in the lawn mower deck.

Determination of the stubble effect on flow parameters

The stubble on the ground creates an additional hydraulic resistance for the deck flow. Obviously the resistance has a maximum in a direction that is parallel to the ground whilst in the normal direction to the ground it is close to zero. In the computational domain this additional resistance can be defined by an additional anisotropic force tensor in a bottom volume under the blade. To select the anisotropic force tensor component the auxiliary computational tests were completed for the flow passed the stubble. The stubble is modeled by a set of small plates (grass blades). For determination of the tensor components a set of tests are completed with different flow velocity under the stubble. Additional resistance tensor components in the near-ground stubble layer are selected to fit the model flow parameters. This enables to account stubble resistance effect with saving processor resources.

Boundary Condition

One has to account particularities of grass – rigid-surface (deck, ground, blade) interaction modeling.

First of all the dry grass practically does not adhere to the deck surface, thus one can assume a full repulsion on this surface. As the real grass particles are not spheres, the repulsion is not resilient. That is taking into account by a coefficient of the velocity normal component recovery. The similar boundary condition is applied on the blade.

The second particularity is taken place between the deck and blade (narrow gap), where the grass particles cannot penetrate because of its relatively higher dimensions. Thus they interact with this domain like with a rigid wall.

The third particularity is in the particles – ground interaction. As the actual grass particles are rather long they cannot return back to the flow part when coming into stubble. This arises from a small flow velocity in the stubble zone and cohesion of grass blades. Thus on the ground one needs to put outlet particles boundary condition (particles are moved off when touching the ground).

COMPUTATIONAL PROCEDURE

Computational approach applied is “moving body”-numerical technology: The problem is solved in the absolute frame of coordinates. The computational mesh changes during the blade passing.

Computations can be made in 4 stages: a) Computation of the incompressible medium with getting average values of energetic parameters and air flow rate definition; b) Determination of source function in equation (2), c) solution of the acoustic-vortex wave equation (2), d) Computation of 2-phase flow. The d) stage computation is made in the domain bounded by the deck wall and deck-ground slot for economy of processor resources.

Initial conditions are zero pressure and velocity in the whole domain.

In the first stage unsteady flow velocities are defined from velocities of blade surface crossing the corresponding cells. At the outlet boundary the normal velocity is taken from the internal nodes and pressure is constant. To improve the accuracy of the unsteady pressure prediction, the resulting solution of the first stage is used as the initial condition for the second stage where unsteady pressure is defined from the change of cell volumes during the blade passage. The results of the first stage are also used to define boundary conditions for 2-phase air-grass flow modeling in the d) stage (air flow rate definition). In the c) stage the infinite impedance condition is put on the wall and blade. On the outlet boundary the specific acoustic impedance equals unity.

COMPUTATIONAL RESULTS

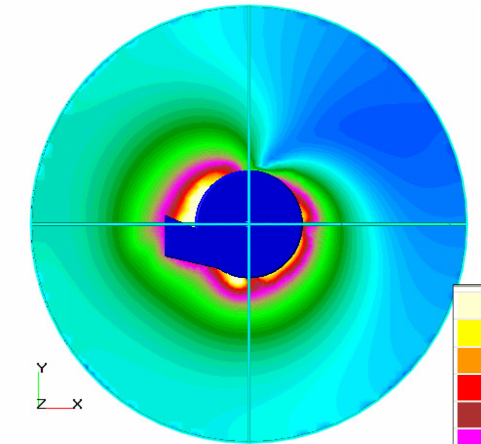
Sound Power prediction

Computations are completed on double processor work station with 2 Gb RAM for a simplified lawn mower deck. The blade of 0.24 mm radius rotates with 3000 RPM.

The computational domain is made like semi-sphere of 1 m radius.

By CFD – CAA computations pseudo-sound pressure pulsation and near sound field data are obtained in the whole computational domain.

Below are presented distributions of pressure pulsation amplitude for the 1st BPF tonal component (100Hz) in different planes by heat color maps. The maximum scale value is ≥ 2 Pa



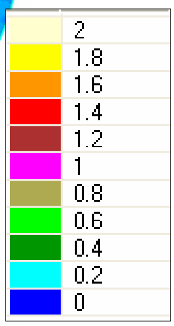


Figure 1: 1st BPF amplitude. Plane view

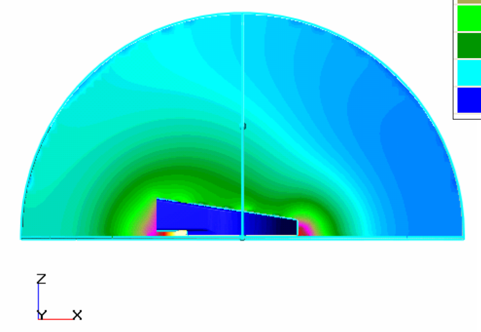


Figure 2: 1st BPF amplitude. Side view

The amplitude distribution shows a noise emission is higher in a direction of the deck exhaust. Having amplitude data enables to determine sound intensity map and sound power as an integral of sound intensity over the outlet boundary of computational domain.

Sound power of BPF harmonic on the outlet area of computational domain is calculated by the formula

$$J = \iint_S \frac{A_f^{\,2} R}{2\rho C (R^2 + Y^2)} ds \text{, [W], where}$$

S – outlet cross-section area;

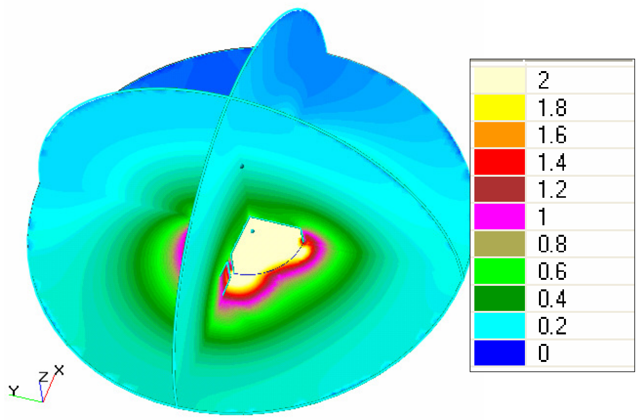


Figure 3: 1st BPF amplitude. Isometric-view (lawnmower deck is removed)

ρC – air wave resistance;

A_f – BPF amplitude;

R,Y – resistive and reactive part of the outlet boundary specific acoustic impedance. At the outlet boundary it is taken

$$Z = R + iY = (1,\ \ 0)$$

Sound power level in dBA scale is determined by formula

$$L = 10\log(J/10^{-12}) - \Delta L$$

Where ΔL is 20dB for the first BPF harmonic component.

Below is presented a color map of sound intensity on the semi sphere surface at the same frequency (100Hz).

Integration gives sound power level 84dB or 64 dBA

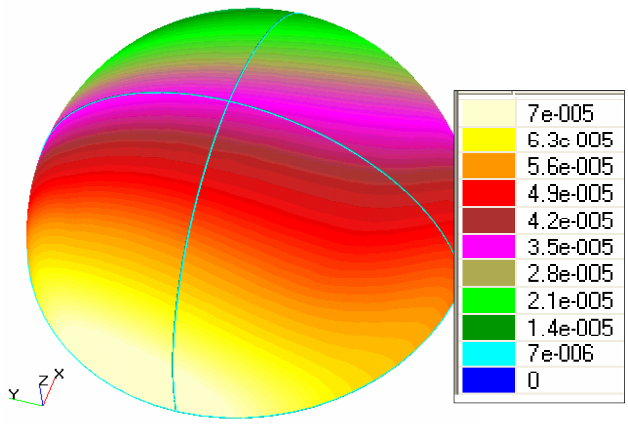


Figure 4: Sound intensity map (W/m²)

Air-Grass Flow Patterns

A flow type in the lawnmower has an axial – radial nature. After intake the flow goes into the deck in a radial direction, then due to the blade action it gets swirling and goes axially, finally in direction to the outlet the flow goes in a radial direction. Thus one can characterize the lawnmower as a mixed flow type hydraulic bladed machine. Due to complexity of flow, it has essential 3D patterns reflecting on energetic characteristic and grass particles motion.

Further computations are completed to model air-grass flow in the presented deck design with taking into account air flow rate obtained by previous calculations. Even under directly defined air flow rate air-grass flow parameters converge slowly much slowly to a steady oscillatory levels. Convergence is controlled by particle mass flow rate through the deck exhaust section. It takes at least 0.5 second of physical time.

Below one can see in **Figure 5** instantaneous grass particles tracks in the deck volume.

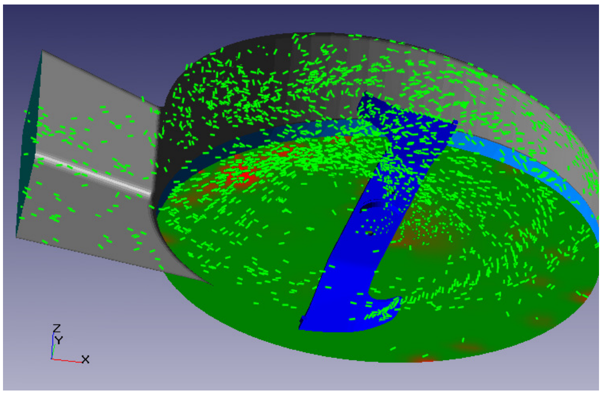


Figure 5: Grass particles in the deck volume

Additional data shown in figures 6 and 7 characterizes evacuation of grass and its fall to the ground surface.

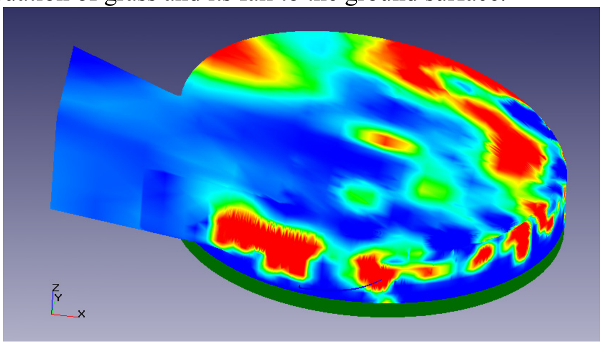


Figure 6: Grass concentration near the deck wall

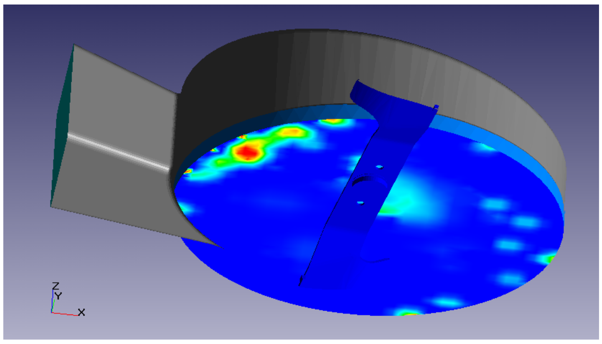


Figure 7: Grass concentration near the ground level

CONCLUSIONS

Computational method for air-grass flow modeling in lawn mowers now accompanies the acoustic-vortex numerical procedure elaborated for sound power prediction in noise modeling of rotating bladed machines with subsonic flow. Both methods can give a more complete data regarding unsteady flow parameters of the lawn mower, its energetic characteristics, grass cutting quality and sound amplitude, intensity and power data.

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