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NUMERICAL AND EXPERIMENTAL STUDY OF 3D UNSTEADY FLOW IN A LAWN MOWER FOR PREDICTION OF PRESSURE PULSATION AND NOISE

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SUMMARY

Experiments fulfilled in CETIM have shown that tonal blade-passing-frequency (BPF) noise becomes predominant for lawn-mowers with a big rotor diameter. 2-D and 3-D CFD unsteady computations give a clear picture of pseudo-sound perturbation inside the casing of lawn-mower. Method of representation of unsteady motion of compressible fluid with subsonic flow as a sum of vortex mode (pseudo-sound) and acoustical mode (airborne sound) is used to define the sound near field.

INTRODUCTION

Systematic measurements and source ranking, carried out on lawnmowers of various sizes with different types of drives (electric motors and combustion engines), have shown that blade noise becomes predominant on big machines (typically for cutting widths more than 50 cm). Simplifying the problem and not taking into account presence of grass, the lawn mower can be considered as a ventilator of mixed – flow type. Due to a small number of blades (usually there are only 2 or 3 blades with cutting surfaces) flow parameters oscillate with blade passing frequency while the velocity field has an apparent 3-dimensional character inside the casing with reverse flows near the outlet section of the machine. In close vicinity of rotor blades, flow patterns resemble those of a centrifugal machine. It gives a possibility to apply 2-D acoustic-vortex approach for preliminary estimation of pressure pulsation and noise emission. Method of representation of unsteady motion of compressible fluid with subsonic flow as a sum of vortex mode (pseudo-sound) and acoustical mode (airborne sound) is developed for 3-D computation as well.

EXPERIMENTAL TEST RIG

A special test rig [1] has been built in order to study the blade noise independently from engine noise and blade-deck interactions. The blade is driven by a silent electric motor, placed below the floor plate. A deck-engine assembly can be positioned above the blade without any direct, structural coupling. A circular segment of the floor plate with 18 pressure transducers along the radius enables to determine the pressure field at the floor level.

The important result obtained is that the sound power level emitted by a lawn mower on blade passage tones is about 10 dB higher than that obtained by measurements on the "opened" rotor (without the volute casing). It indicates the necessity of well-designed flow part of the machine to reduce hydrodynamic unsteady interaction and noise generation between the rotor and casing.

COMPUTATIONAL APPROACH

Governing equations

For prediction of airborne sound in the near field the mathematical model is based on a representation of fluctuating flow velocity field **V** as a combination of vortex and acoustic modes [2, 3],

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

Where

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

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

φ - Acoustic potential

This gives an acoustic-vortex wave equation relatively enthalpy oscillation $\boldsymbol{i}$ in the isentropic subsonic flow of compressible fluid.

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

Right side of this equation represents the source function, defined from the velocity field of vortex mode flow. It is determined from the solution of unsteady equations of incompressible fluid with appropriate boundary conditions.

Numerical methods

For analysis of the problem, 2D code Harmony [2] and 3D code FlowVision [4, 5] are used.

In 2D analysis vortex mode flow is computed in 2 steps. In the first step the flow around rotor is defined by discrete vortex method with applying "sliding-break-point" conditions on blades. In the second step unsteady Euler equations are solved for turbulent flow in the volute casing. Then disturbing function of the wave equation is defined from unsteady velocity field of the vortex mode. The computational procedure is the same as for centrifugal ventilators [3] and pumps [1, 5].

The 3D numerical procedure is based on non-staggered Cartesian grid with adaptive local refinement and a sub-grid geometry resolution method for description of curvilinear complex boundaries [4]. For vortex mode flow, unsteady Navier-Stokes equations are solved with applying k-ε turbulence model. Iterative procedure goes up to convergence to a periodical solution and subsequent definition of the disturbing function. Initial condition is zero pressure and velocity in entire computational domain. On rigid walls the logarithmic velocity profile is applied as a boundary condition for the turbulent flow. At the outer boundary free-outlet flow condition is used with linear extrapolation of velocity from inner nodes.

Finally wave equation is solved relatively to pressure oscillation using an explicit numerical procedure. Zero pulsatory pressure is an initial condition for solution of wave equation. Casing and rotor walls are assumed absolutely rigid and infinite impedance is defined on all rigid walls. At the outer boundary the specific acoustic impedance equals unity.

RESULTS OF 2D COMPUTATION

2-Dimensional flow analysis shows pseudo-sound perturbations due to intensive vortex creation on blade tips [1]. Wake zones rotating with blades create pressure fluctuations on blade passing frequency and its higher harmonics. It is found that intensity of wake zones essentially depends on blade shape and number of blades and it is found that considerable reduction of pressure pulsation (by 3 – 5 times) will be reached by changing the blade shape, number of blades from two to three and increase of the volute radial gap [1].

Thus experimental and computational studies show a big importance of optimal profiling of the fluid part of lawnmower to reduce noise level.

RESULTS OF 3D COMPUTATION

Computational domain is a cylinder with diameter 1.5 m and height 0.75 m shown in Figure 1.

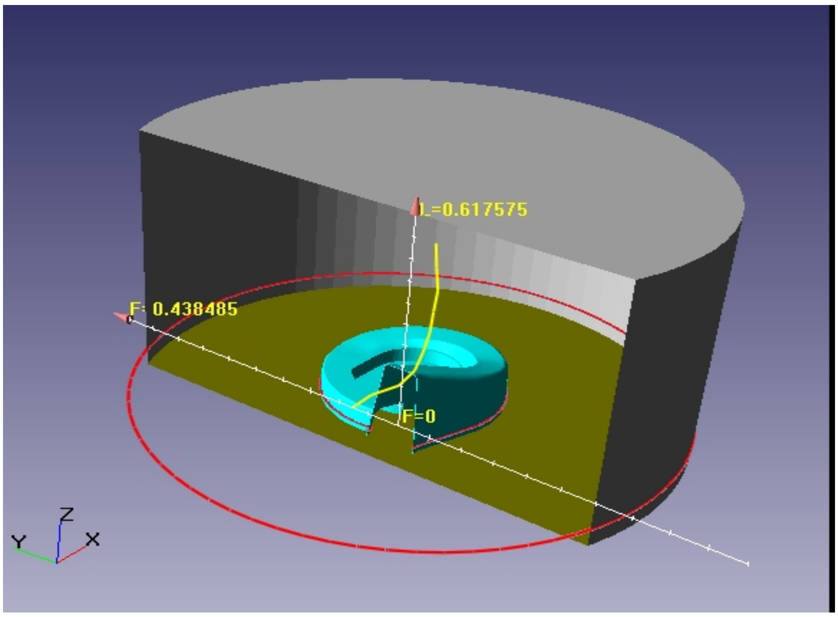

Figure 1: Computational domain

The bottom of the cylinder is considered as a rigid wall. Side and top surfaces form the outlet boundary.

Grid generation procedure produces a rectangular grid with local multilevel adaptation. The mesh is automatically adapted in volute region resulting in more accurate simulation. The original cell is divided into 8 equally size cells (1st adaptation level). Furthermore the resulting cell can be divided again (2nd adaptation level) and so up to the required level of accuracy. The sub-grid resolution method is used 'to fit' the Cartesian grid to the geometrical boundary in order to accurately describe the boundary conditions. It is especially important for the blade that represents a relatively thin and curved surface. The initial "parent" rectangular cell is cut off by the curvilinear surface and the parent cell is disjoined into new volume elements formed by the facet surface and the original grid cell faces.

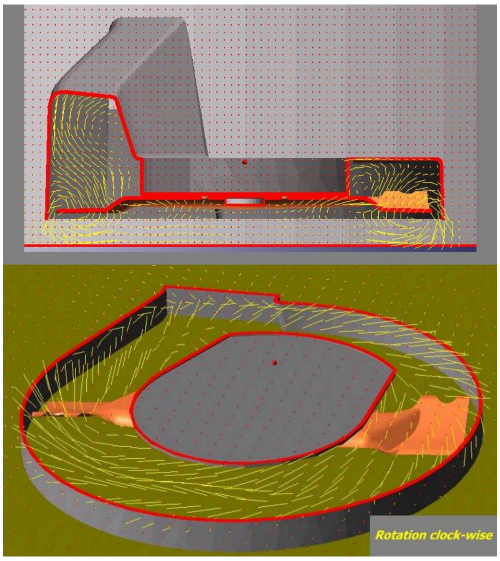

Figure 2: Unsteady velocity field

Unsteady velocity field presented in Figure 2 has an essential 3D nature with intensive secondary flow around the blade and the recirculation flow in the outlet section of the volute (see Figure 3). The last is an additional powerful noise source and requires a well-designed outlet part of the machine.

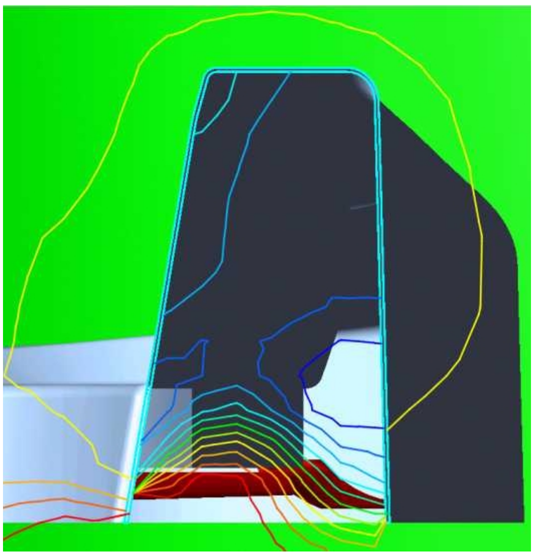

Figure 3: Recirculation zone (isolines from green to red color) at the outlet

The secondary flow around the blade and Coriolis forces form in the relative motion frame a characteristic jet-wake distribution of pressure near the blade, as it is shown in Figure 4.

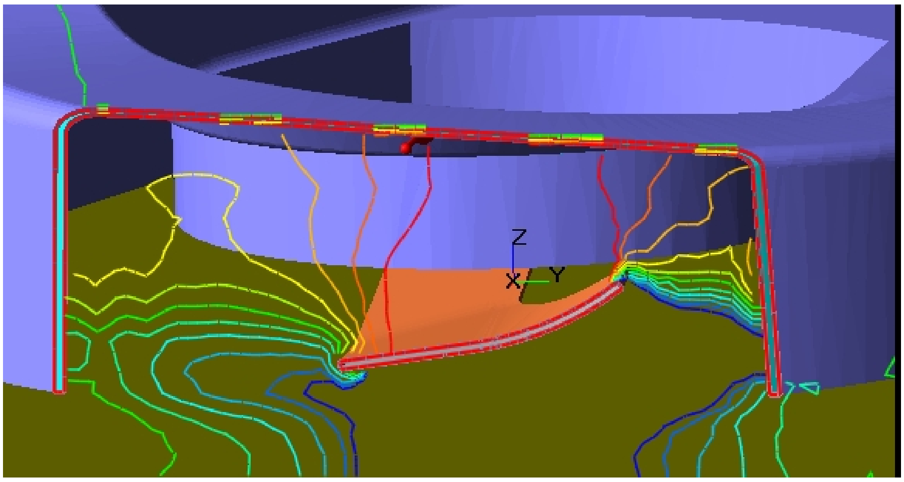

Figure 4: Unsteady pressure field near the rotating blade

On the pressure side of the blade there is a zone of higher pressure. Under the blade, on the suction side there is a zone of lower pressure.

Such a pressure distribution rotates together with the blade and creates a characteristic unsteady pseudo-sound field in the bottom level of the volute casing shown in Figure 5.

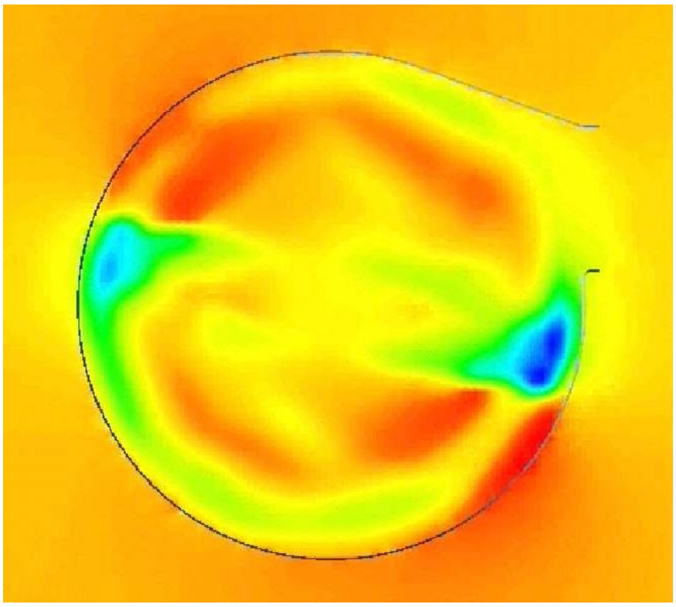

Figure 5: Unsteady pressure field

In the absolute reference frame each blade passage brings a sharp negative pressure peak. The greater amplitude takes place at the beginning of volute under the small radial gap.

The averaged computed pressure is compared with stationary pressure measurements as it is outlined in Figure 6. It proves the fact that the unsteady computation brings a right flow-rate vs. power characteristic of the machine. That is also confirmed on a diagonal pump [5], when the exact head characteristic has been obtained in a wide range of flow rate. .

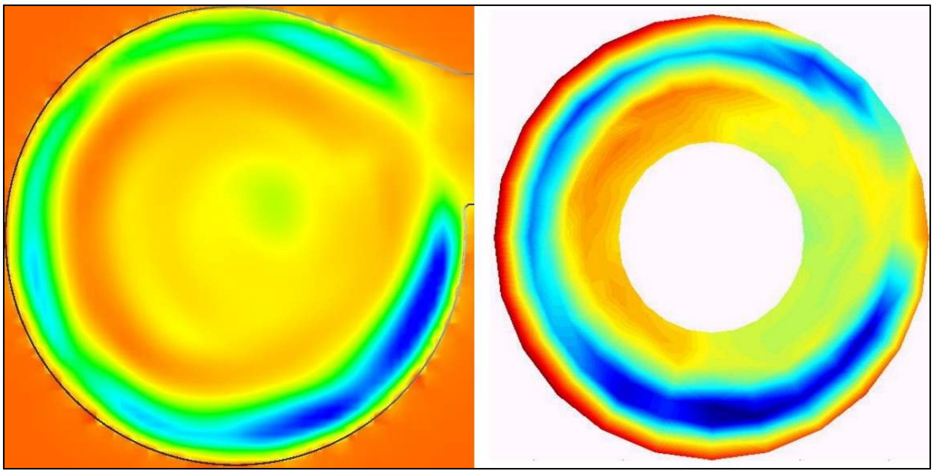

Figure 6: Averaged pressure; Computed (left) and measured (right)

Due to a big non-uniformity of flow parameters, integral characteristics of the lawn mower experience big oscillations with the blade passing frequency.

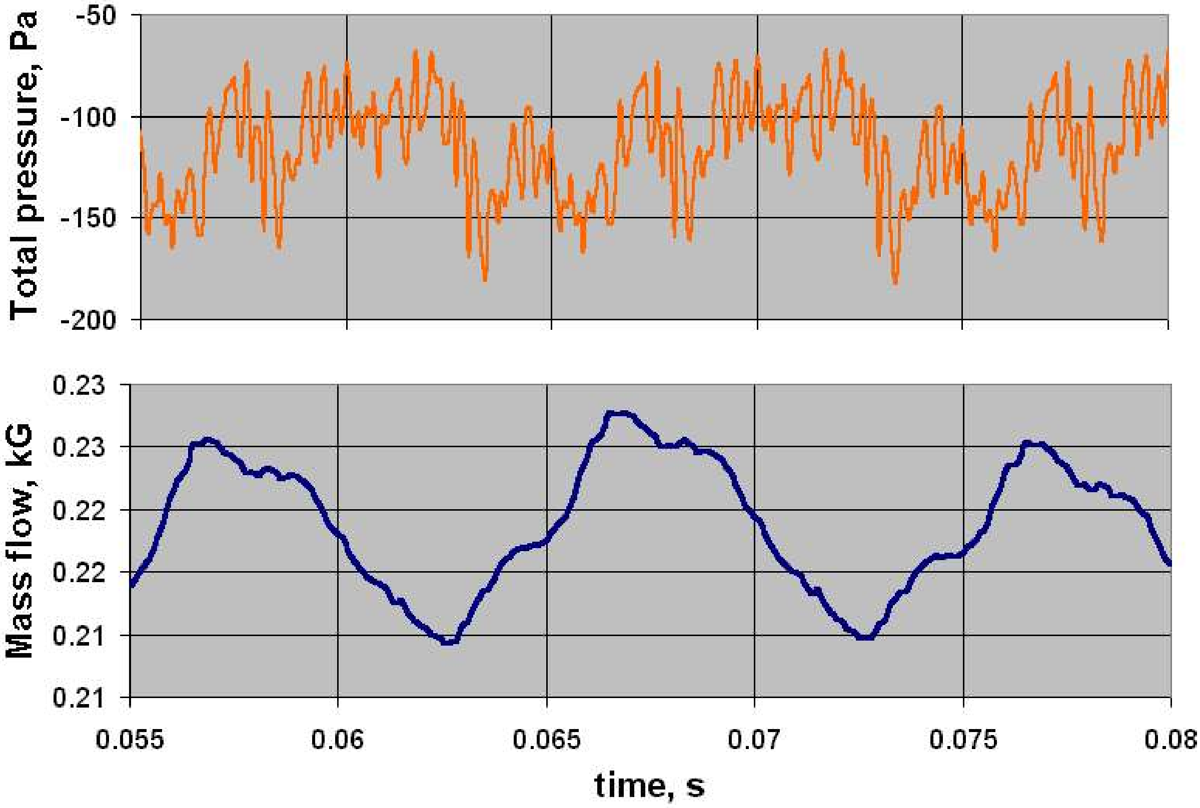

Figure 7: Computed total pressure and mass flow at the inlet

One example of such an oscillation is presented in Figure 7. One can see an oscillation of the mass flow and total pressure (flow-weighted and area-averaged) at the inlet circular cross section of the volute casing. It proves that a part of sound power of the lawn mower is generated by the source of monopole type. This source is caused by the recirculation flow in the outlet part of the lawn mower.

Distribution of BPF amplitude of the source function (right side of equation 2) is outlined in Figure 8. There is a plot along the line L_2 that is parallel to and goes near the top boundary and another plot along the line L_1 starting from the outlet section and perpendicular to the line L_2. Scales of plots are different because of big difference of the amplitudes.

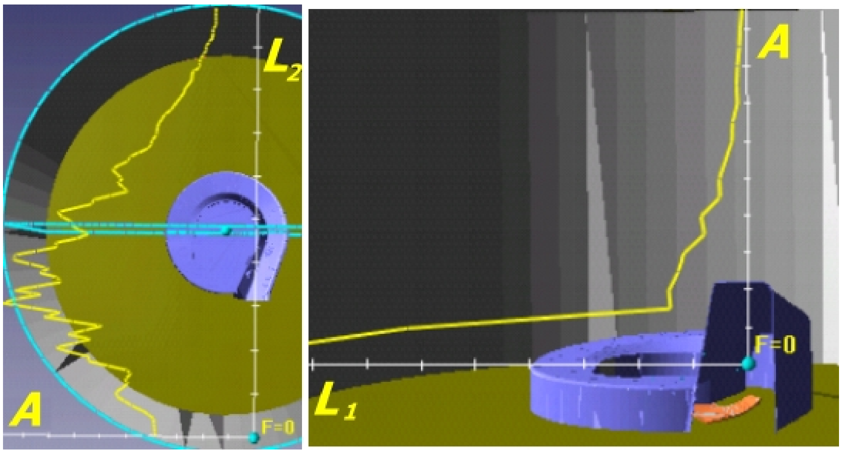

Figure 8: 1st BPF amplitude of source function on top (left) and outlet (right)

Thus the source of BPF noise is shifted to the outlet part of the lawn mower and rapidly attenuates with increase of the distance from the machine.

Oscillatory part of the pressure field resulting from solution of wave equation in a certain time moment is presented in Figure 9. The plane of this representation is shown in Figure 1 by a red circle section.

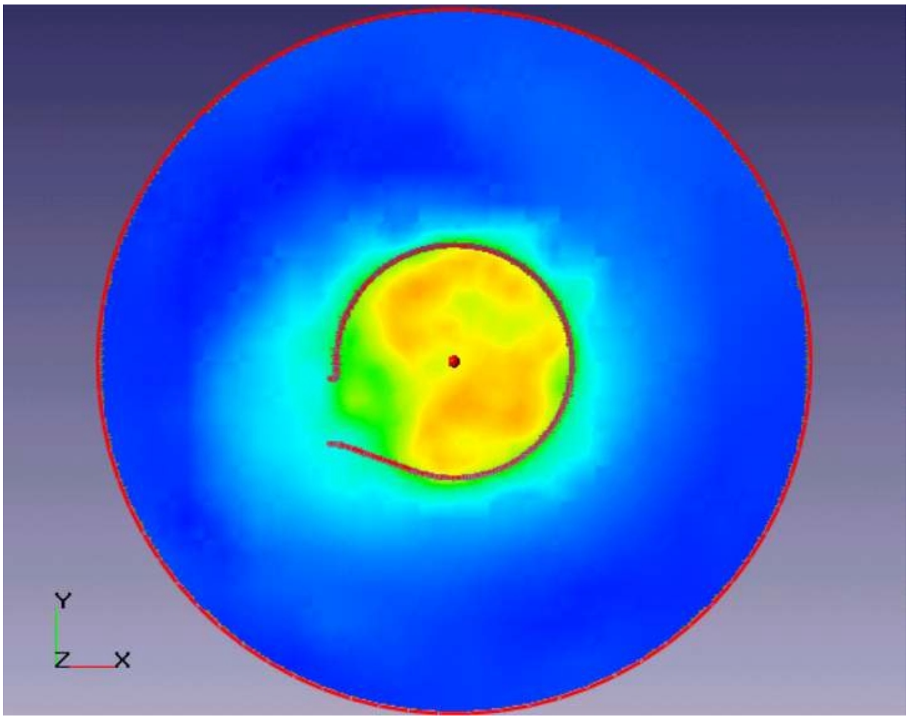

Figure 9: Oscillation pressure field near the ground level

One can see that the pressure field consists from a pseudo-sound zone in the volute casing and diffuse sound field near the lawn mower. Pseudo-sound oscillation is generated directly by rotating blades and the amplitude here is equals to the pressure differential on the blade – about 1000 – 1500 Pa. Near field is created by unsteady fluid motion in vicinity of the casing, outlet air jet and recirculation, emission of sound waves from the exhaust section and from the gap between the casing and the ground.

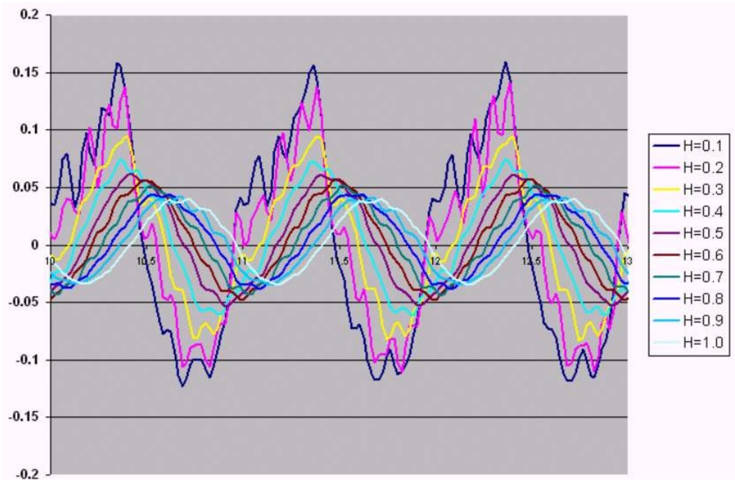

Figure 10: Pressure signal on different distances

The change of pressure signal near the outlet section is shown in *Figure 10*. The pressure signal reduced by a fluid density multiplied by blade tip velocity squared. Location of points where signals are registered is outlined in figure 7. Points are uniformly distributed along the vertical line near the outlet section. On the plot, the H=0.1 corresponds to the lowest point and H=1.0 gives the top point.

One can see the pressure signal becomes more "sinusoidal" with attenuation of amplitude and change of phase. In the pseudo-sound zone (H=0.1—0.3) phases of signal are closely related.

CONCLUSION

The method for prediction of 3-D near sound field in lawn mowers and ventilators is developed on the base of acoustic-vortex representation.

BIBLIOGRAPHY

[1] M. Bockhoff, K. Mones, S. Timouchev, K. Ilhichov, A. Aksenov *Experimental and Computational Study of Unsteady Flow and Noise in a Lawnmower Casing.* 5th European Conference on Noise Control, 19-21 May **2003**, Naples, Italy

[2] Timouchev S., Tourret J. *Numerical Simulation of BPF Pressure Pulsation Field In Centrifugal Pumps*. 19th International Pump Users Symposium, February **2002**, Houston, Texas

[3] S. Timouchev, K. Ilhichov, J. Tourret *Numerical Studies Of BPF Pressure Pulsation In Centrifugal Ventilators*. Colloque: Bruit des Ventilateurs à Basse Vitesse, l'Ecole Centrale de Lyon, 8 et 9 novembre, **2001**

[4] Aksenov A.A., Dyadkin A.A., Gudzovsky A.V. *Numerical Simulation of Car Tire Aquaplaning*. Computational Fluid Dynamics '96, J.-A. Desideri, C.Hirsch, P.Le Tallec, M.Pandolfi, J.Periaux edts, John Wiley&Sons, pp. 815-820, **1996**

[5] Serguei Timouchev, Gal de Botton, Avi Reznik *Experimental and computational study of pressure pulsation in a centrifugal pump. 10th International Congress on Sound and Vibration, 7 10 July* **2003**, Stockholm, Sweden