NUMERICAL SIMULATION OF THE AERODYNAMIC TONAL NOISE GENERATION IN A BACKWARD-CURVED BLADES CENTRIFUGAL FAN

PACS REFERENCE: 43.28.Ra

Velarde, Sandra; Fanjul, Raquel; Ballesteros, Rafael; Santolaria, Carlos; Fernández, Joaquín
Universidad de Oviedo. Área de Mecánica de Fluidos
E.T.S. Ingenieros Industriales e Ingenieros Informáticos. Campus de Viesques
33271 Gijón. Asturias
España
Teléfono: +34 985182101
Fax: +34 985182098
E-mail: sandrav@correo.uniovi.es

ABSTRACT

In this work, a numerical study about the aerodynamic tonal noise generation in a centrifugal fan has been carried out. A three-dimensional simulation of the unsteady flow on the whole impeller-volute configuration has been performed. The numerical results have been compared with previous experimental results obtained in the same machine. The study has been focused on the impeller-volute interaction phenomena, analysing the influence of the distance between the impeller and the volute tongue. Then, the vortex noise equation formulated by Powell (1964) has been used to show the zones in which the tonal noise generation is concentrated and how this generation changes when the operating conditions are modified.

INTRODUCTION

Most of the studies on aerodynamic noise generated by moving blades are based on the acoustic analogy (Lighthill, 1952). This theory considers the flow field as a superposition of a small amplitude fluctuating sound field and a nonperturbed aerodynamic field that generates the fluctuating field. Powell's theory of vortex sound (1964) is an alternative to Lighthill's analogy, which expresses noise generation as a function of velocity and vorticity fields. Thompson and Hourigan (1992) made a prediction of the blade passing tone of a centrifugal fan by solving Powell's wave equation using a finite element method. The acoustic forcing term was derived from experimental velocity data obtained by Shepherd and Lafontaine (1992) using a Particle Image Velocimetry (PIV) method.

In this work, a numerical study about the aerodynamic tonal noise generation in an industrial centrifugal fan with backward curved blades has been carried out. A three-dimensional numerical simulation of the complete unsteady flow on the whole impeller-volute configuration has been performed. Special attention has been focused on the impeller-volute interaction phenomena, analysing the influence of the distance between the impeller and the volute tongue. The numerical results have been contrasted using previous experimental investigations carried out in the same machine. The acoustic forcing term in the right hand of the vortex noise equation formulated by Powell (1964) has been calculated. The results of this numerical simulation show the zones in which the tonal noise generation is concentrated and how this generation changes when the operating conditions are modified.

NUMERICAL PROCEDURE

A three-dimensional numerical simulation of the complete unsteady flow on the whole impeller-volute configuration of a centrifugal fan has been carried out. Calculations have been performed with a commercial software package, FLUENT®. This code uses the finite volume method and the 3D Navier-Stokes equations are solved on an unstructured grid. The unsteady flow is solved using a sliding mesh technique, which has been successfully applied to turbomachinery flows (González et al., 2002).

The code solves the fully 3D incompressible Navier-Stokes equations, including the centrifugal force source inside the impeller and the unsteady terms. Turbulence is simulated with the standard k-ε model. Although grid size is not adequate to investigate local boundary layer variables, global ones are well captured. For such calculations, wall functions, based on the logarithmic law, have been used. The time dependent term scheme is second order, implicit. The pressure-velocity coupling is calculated through the SIMPLEC algorithm. Second order, upwind discretizations have been used for convection terms and central difference schemes for diffusion terms.

The code was run in a cluster of twelve Athlon-K7 (1.2 GHz) nodes. The time step used in the unsteady calculation has been set to $2.24 \cdot 10^{-4}$ seconds in order to get enough time resolution for the dynamic analysis (Courant number was kept below 2, which assures very good time accuracy and numerical stability). The impeller grid movement is related with this time step and the rotational speed imposed (ω=155 rad/s), so a complete revolution is performed each 180 steps.

EXPERIMENTAL EQUIPMENT

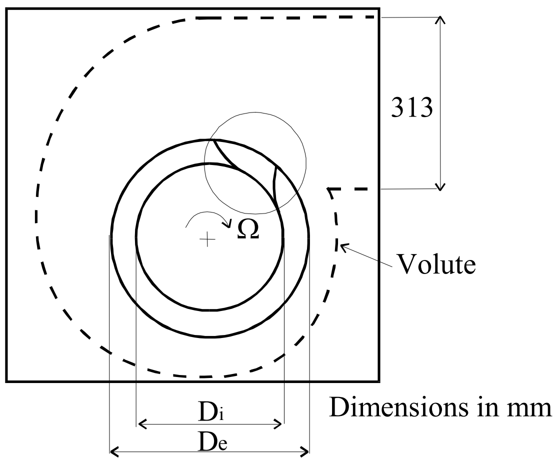

Figure 1. Tested fan sketch

The tests and numerical simulations have been made on a simple aspirating centrifugal fan driven by an AC 9.2 kW motor rotating at 1480 rpm, with a fluctuation level lower than 0.5 percent for the whole range of the analyzed flow rates. The two shrouded rotors tested have 10 backward curved blades with outlet diameters of 400 and 355 mm. The minimum distances between the impeller and the volute tongue are respectively 12.5 and 21.3 percent of the outlet impeller diameters. The volute has a width of 248 mm. Figure 1 shows a sketch of the fan. The tests for the aerodynamic and acoustic characterization of the fan have been made in a normalized ducted installation. More details about procedures and impellers dimensions have been reported in previous works (Velarde-Suárez et al., 1999, 2000a, 2000b and 2001).

In this work, we have focused the attention on the tonal aerodynamic noise generated at the blade passing frequency (in the 250 Hz band for this fan). Similarity laws have been applied to compare the tonal aerodynamic noise levels of the two impellers tested. The specific sound power levels (*SWLs*) defined by Madison (see Neise, 1992) have been calculated and represented in figure 2, in order to compare both impellers tested.

$$SWLs = SWL - 10\log Q - 20\log P_T \qquad (1)$$

where *SWL* is the sound power level in dB, *Q* is the flow rate in m^3/s and P_T the total pressure increase in Pa. Specific *SWL* evolution is very similar in both impellers, with a minimum generation zone coincident to the best efficiency operating zone. (The best efficiencies were obtained for flow coefficients φ=0.07). This minimum noise generation zone is wider for the 355 mm-diameter impeller. Lower noise levels were observed for the 355-diameter impeller, with a

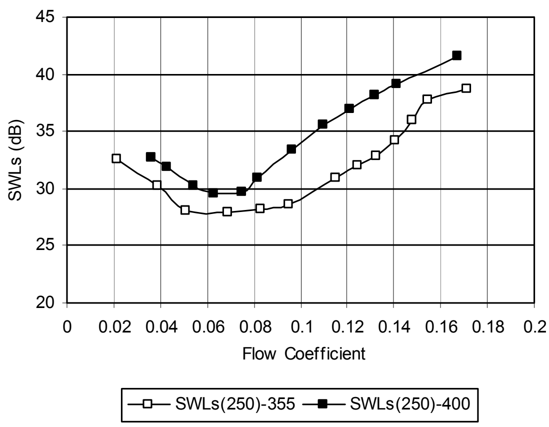

Figure 2. Specific SWL at blade passing frequency versus the flow coefficient

greater impeller-tongue gap, associated to lower amplitudes of pressure fluctuations near the tongue. This study is focused on flow rates higher than the best efficiency point, because it is the operating range with a stronger tonal noise generation.

EXPERIMENTAL AND NUMERICAL RESULTS

The method described above has been employed to make a comparison for both the numerical and experimental performance curves for the tested fan. The numerical data are obtained after averaging the values of the unsteady calculation. In figure 3, the numerical and experimental performance curves for the two impellers tested are compared. Several flow rates have been simulated and represented in these figures. The flow rates simulated have been selected mostly from the zone with a greater tonal noise generation. The total pressure coefficients obtained in these points matches quite well with the experimental ones, especially for the 400 mm-diameter impeller. In a previous 2D simulation of this fan (Velarde-Suárez et al., 2000), the agreement between numerical and experimental results were not so good, showing the importance of considering the three-dimensional effects in the flow fields.

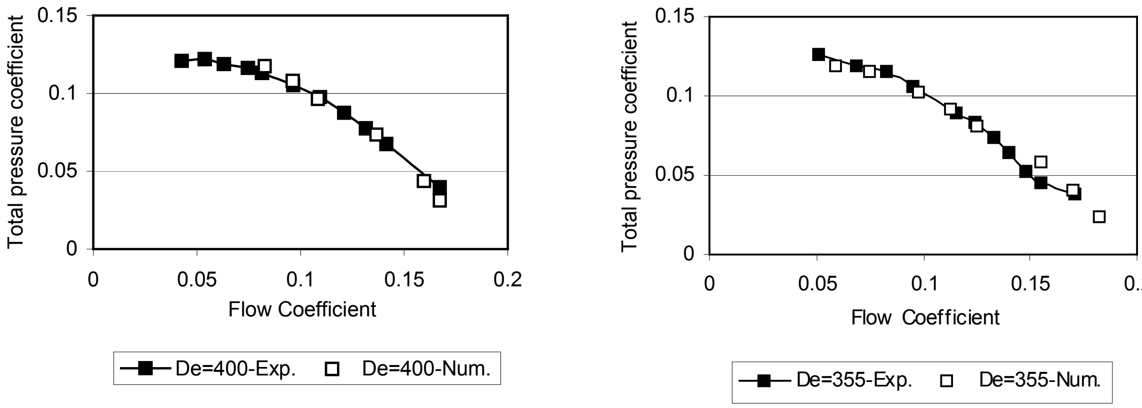

Figure 3. Comparison between numerical and experimental performance curves

The aerodynamic tonal noise generation of the fan could be calculated by solving the full compressible time-dependent Navier-Stokes equations. This is a very difficult and computationally expensive task, principally due to the mismatch of acoustic and flow timescales. However, the methods based on the acoustic analogy (Lighthill, 1952) assume that, at low Mach numbers, the acoustic (compressible) part of the flow can be decoupled from the incompressible flow (irrotational, plus vortex-induced). The acoustic problem is much easier computationally but the source term, which is a function of the flow field, also needs to be determined.

The unsteady numerical simulation described above has been employed to calculate the time-dependent velocity and vorticity fields both in the impeller and in the volute. Then, a numerical routine has been implemented in order to calculate the acoustic forcing term in the right hand of the vortex noise equation formulated by Powell (1964). This equation expresses the generation of aerodynamic tonal noise as a function of the "incompressible" velocity and vorticity fields:

$$\frac{1}{c_o^2}\frac{\partial^2 p'}{\partial t^2} - \Delta p' = \rho_o \nabla(\vec{\omega} \times \vec{u}) \tag{2}$$

where:

p'	Acoustic pressure fluctuations in the far field
$\vec{u}$, $\vec{\omega}$	Velocity and vorticity fields, in which the acoustic fluctuations have been removed
c_0 , ρ_0	Sound speed and density of the mean flow

Using the numerical results of velocity and vorticity, the acoustic source term (right hand of equation 2) has been calculated. In figures 4 to 9, some results of the calculated acoustic source term are shown. The term has been represented in a non-dimensional way, divided by the rotational speed squared and the density.

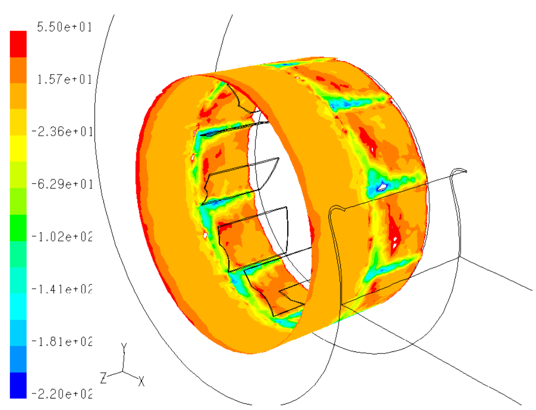

Figure 4. Contours of acoustic source term, R=210 mm, 400-mm impeller diameter, φ=0.07

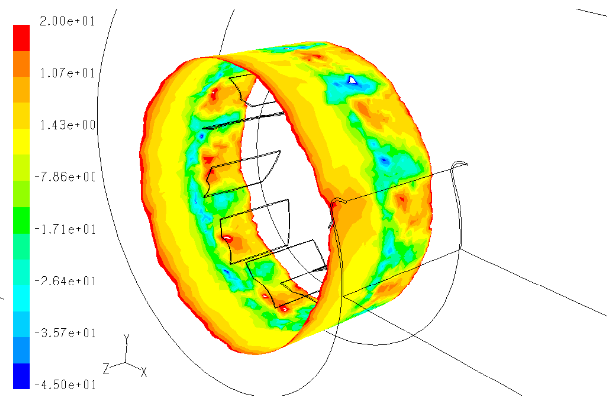

Figure 5. Contours of acoustic source term, R=225 mm, 400-mm impeller diameter, φ=0.07

In figures 4 and 5, the contours of the acoustic source term have been plotted on two cylindrical surfaces located at distances of 10 and 25 mm of the 400-mm impeller outlet (the last one, approximately at midway between the impeller outlet and the volute tongue). These figures show the spatial distribution of the acoustic source term for an impeller position. The acoustic term shows higher values in the surface nearer to the impeller outlet. The principal sources of noise appear at the blades outlet. Strong sources of noise appear also in the separated flow zones near the front and back impeller plates. The interaction between the impeller and the volute tongue is more clearly showed in figure 5.

In figures 6 and 7, the contours of the acoustic source term for an impeller position have been plotted in the middle planes of the 400 mm impeller. Two flow coefficients have been chosen in these figures: the best efficiency one (φ =0.07) and a very high value (φ =0.17).

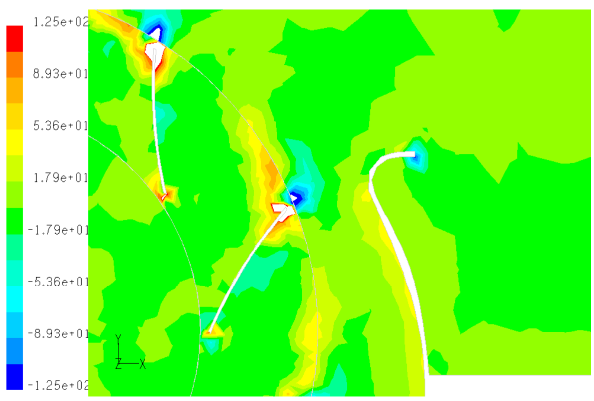

Figure 6. Contours of acoustic source term, middle plane, 400 mm impeller diameter, φ=0.07

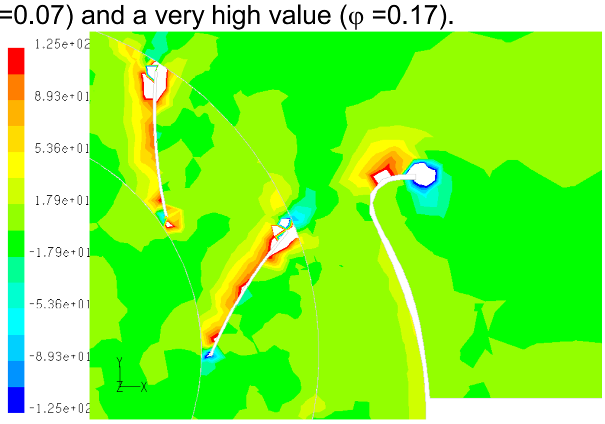

Figure 7. Contours of acoustic source term, middle plane, 400 mm impeller diameter, φ=0.17

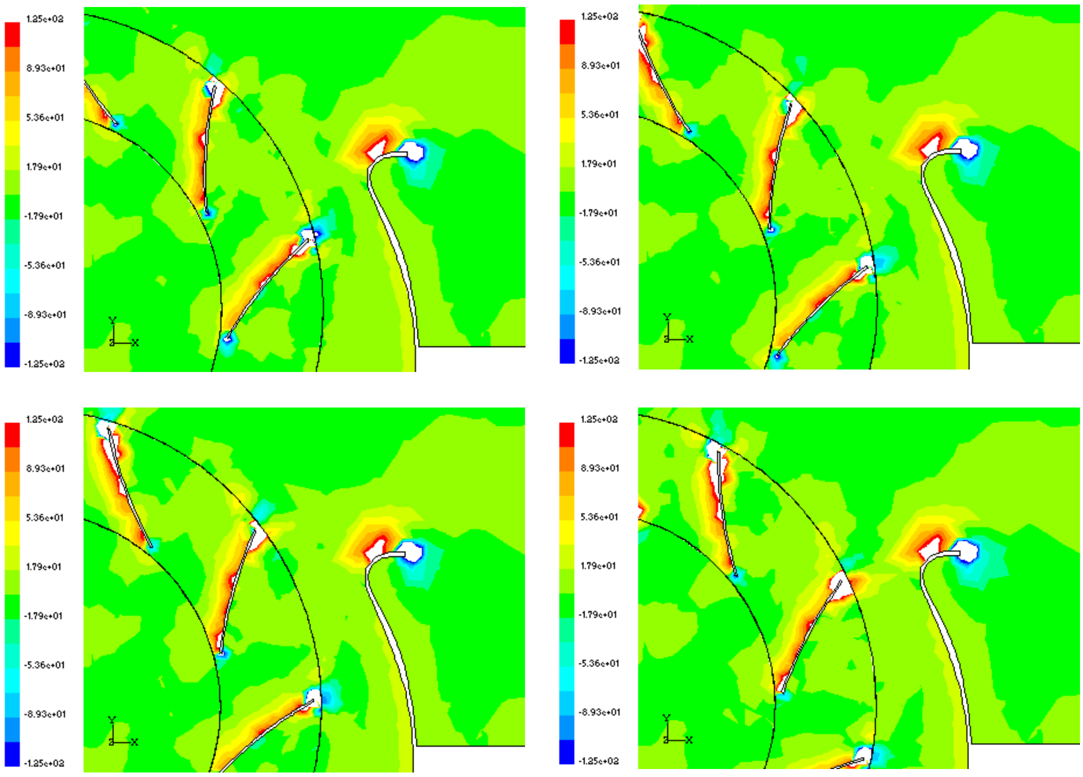

Figure 8. Time evolution of the acoustic source term, 400-mm impeller diameter, φ=0.17

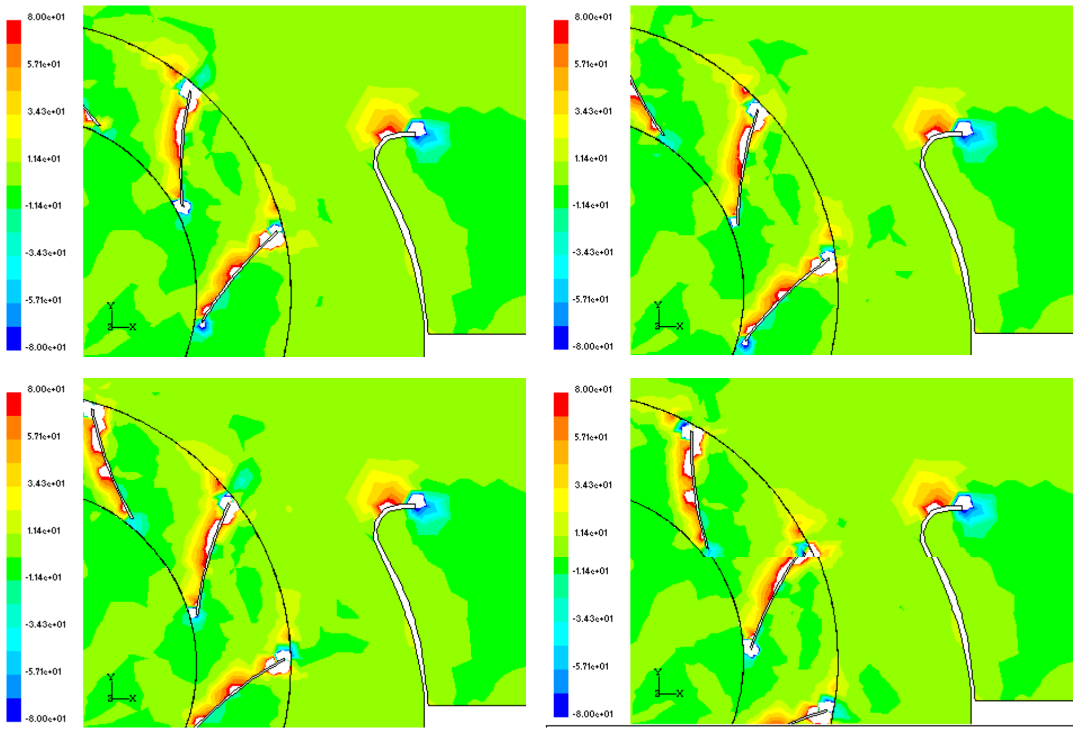

Figure 9. Time evolution of the acoustic source term, 355-mm impeller diameter, φ=0.17

In figures 8 and 9, four impeller positions have been chosen to show the time evolution of the acoustic source term in the vicinity of the tongue for both impellers. The acoustic source term in this zone presents higher values for the 400-mm impeller, due to the smaller impeller-tongue gap. At high flow rates, a strong acoustic source appear on top of the tongue. The interaction between this source and the originated from the blade outlet is related with important levels of tonal noise at high flow rates showed in figure 2. This interaction effect is visible in both impellers, although more intense in the 400-mm one, as was expected. The interaction between the impeller and the volute, reported in the literature as the main source of aerodynamic tonal noise, is more intense when each blade passes in front of the tongue.

The results presented above provide interesting information for the detection and characterization of the fan noise sources, in order to compare different geometries and to establish criteria for a better aeroacoustic design.

CONCLUSIONS

A three-dimensional numerical simulation of the complete unsteady flow on the whole impeller-volute configuration of a centrifugal fan has been carried out. The numerical results have been contrasted using previous experimental investigations, showing a good agreement.

The vorticity noise sources have been represented and analyzed in order to show the zones in which the tonal noise generation is concentrated and how this generation changes when the operating conditions are modified. As was expected, the interaction between the impeller and the volute tongue is the predominant source of tonal noise in this kind of machines. The generation of tonal noise increases with flow rate and when the impeller-tongue gap is reduced.

ACKNOWLEDGMENTS

This work was supported by the Research Projects DPI 2000-0702-C02-01 and DPI 2001-2598

REFERENCES

González, J.; Fernández, J.; Blanco, E.; Santolaria, C., 2002, “Numerical simulation of the dynamic effects due to impeller-volute interaction in a centrifugal pump", ASME Journal of Fluids Engineering, Vol. 124

Lighthill, M.J., 1952, "On sound generated aerodynamically. I. General theory", Proc. Roy. Soc. A211, pp. 564-587.

Neise, W., 1992, "Review of fan noise generation mechanisms and control methods", Proceedings of FAN NOISE Symposium, pp. 45-56, Senlis, France.

Powell, A. 1964, "Theory of vortex sound", J. Acoust. Soc. Amer., Vol. 16, pp. 177-194.

Shepherd, I.C., Lafontaine, R.F., 1992, “Measurement of vorticity noise sources in a centrifugal fan”, Proceedings of FAN NOISE Symposium, pp. 205-212, Senlis, France.

Thompson, M.C., Hourigan, K., 1992, “Prediction of the noise generation in a centrifugal fan by solution of the acoustic wave equation”, Proceedings of FAN NOISE Symposium, pp. 205-212, Senlis, France.

Velarde-Suárez, S.; Santolaria-Morros, C.; Ballesteros-Tajadura, R., 1999, "Experimental Study on the Aeroacoustic Behavior of a Forward-Curved Centrifugal Fan", ASME Journal of Fluids Engineering, Vol. 121, pp. 276-281.

Velarde-Suárez, S.; Ruiz-Fuertes, P.; Ballesteros-Tajadura, R.; Santolaria-Morros, C., 2000, "Pressure Fluctuations and Generation of Tonal Noise in a Centrifugal Fan", Proceedings of 9th International Symposium on Unsteady Aerodynamics Aeroacoustics and Aeroelasticity of Turbomachines, Lyon, France.

Velarde-Suárez, S.; Ballesteros-Tajadura, R.; Santolaria-Morros, C.; Ruiz-Fuertes, P, 2000, "Estudio de la generación aerodinámica de ruido tonal en un ventilador centrífugo industrial", Número Extraordinario de la Revista de Acústica, Volumen XXXI

Velarde-Suárez, S.; Ballesteros-Tajadura, R.; Santolaria-Morros, C.; González-Pérez, J., 2001, "Unsteady Flow Pattern Characteristics Downstream of a Forward-Curved Blades Centrifugal Fan", ASME Journal of Fluids Engineering, Vol. 123, pp. 265-270.