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Comparison of performance of axial fans with straight and swept blades

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Abstract

Noxiousness of the noise generated by fans applied in different heat power and ventilation systems increase the tendency to develop new fans with the lower level of noise saving the same performance. In this paper the results of investigation of two axial fans WOO-63 with different rotor blades: straight and forward swept are given. This investigation shows that the noise of the fan with swept blades is about 6 dB lower than the noise of the fan with straight blades, but performance of the fan with swept blades remains as for the fan with straight blades.

Keywords: Axial fans, Performance of fans

Nomenclature

a, b – axis of elipse
A, B – parameters
c – chord, m
D – diameter, m
k – parameter of logarithmic spiral, [-]
L_{pA} – noise level, dB
n – rotational speed, rev/min
N – power, kW
r – radius, m
s – circumferential spacing of blades, m
V – volume flow rate, m^3/s

Greek letters

α – angle between the tangent to the spiral and its radius vector

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δ – deviation angle
Δ – difference
ξ – stagger angle
θ – angle of the logarithmic spiral
θ_p – camber of profile
λ – sweep angle
μ – dihedral angle
η – efficiency
σ – solidity

Subscripts

i – in i-th point
w – internal
z – external

1 Introduction

In development of axial fans more and more often the swept design line of blade is preferred to the straight one so that the twist of the blade is caused by the varying stagger angle of profiles along the blade and also they do not lie on the same straight radius line. One of the aims of these new designs is actually a reduction of the noise generated by fan. Non-perpendicular arrangement of the lift element, e.g. wing or blade against the fuselage or rotor is actually nothing new. In aeronautics almost from its down time of development it was resigned from the perpendicular location of the wing because of the stability problems. However, from the fourties of last century the positive sweep of wings is used to reduce the drag by the trans- and supersonic speeds of aircraft. To describe the arrangement of the wing against the fuselage two angles are defined, there are: dihedral and sweep angle [1]. In Fig.1 the sweep λ and dihedral μ angle of the wing relative to the aircraft body is shown after Lewis and Hill [3]. Additionally the sweep of blades in the Francis hydro turbine and in the axial steam turbine is shown. Analyzing the sketches referring to fluid-flow machines it can be seen that even in the Francis turbine and axial steam turbine one has to do with the sweep of blades; in the case of Francis turbine with the forward sweep and in the case of steam turbine with a backward one. In shipbuilding the propellers with strongly swept blades (backwards sweep) are used to reduce the instationary load of bearings, to reduce the instationary pressure affecting hull and increasing cruise velocity, by which the cavitation is occurred at the blade [1].

The concept of applying of swept blades in the fluid machinery was considered surely since the fifties of the last century [7, 3]. In the middle of seventies the NASA, USA, started the program of systematic investigation of compressors with swept blades preferring however the blades with backward sweep. The results of

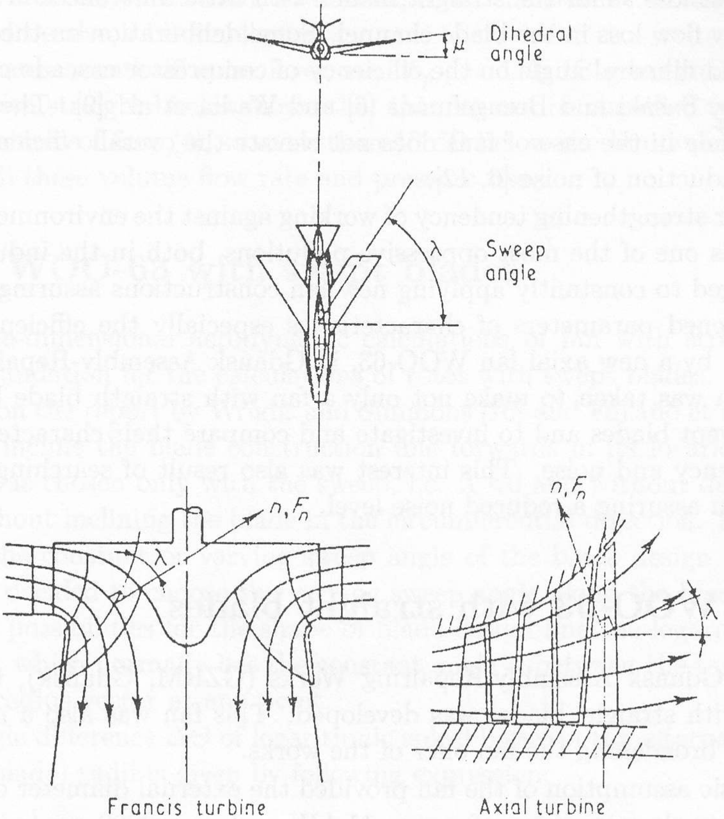

Figure 1. Sweep and dihedral angle of the wing of the aircraft and blades in fluid-flow machines [3].

this investigation was not very promising for the sake of not attaining of planned pressure rise, volume flow rate and efficiency.

Thanks to Wennerstrom [12], at the beginning of eighties of the twentieth century the concept of application of swept blades in transonic and supersonic compressors came back incorporating both forward and backward sweep. For the nominal conditions of run the characteristics of compressors with straight and swept blades were not different from each other, but for the non-nominal conditions of work some parameters of characteristics of compressors with swept blades were better than these with straight blades. In particular applying the blades with backward sweep resulted in better efficiency and surge limit.

According to the investigation results of Walker [10] non-radial location of the blades in rotor (irrespectively sweep or dihedral) resulted in the same amount of total exhaust loss as for the straight blades with little differences in distribution of secondary flow loss in the blade channel. Some deliberation on the comparison of sweep and dihedral angle on the efficiency of compressor cascade can be found in papers by Sasaki and Breugelmans [6] and Wadia et al. [9]. The application of swept blade in the case of fans does not elevate the overall efficiency but only gives the reduction of noise [6, 12].

The ever strengthening tendency of working against the environment pollution and noise as one of the most oppressive pollutions, both in the industry and at home, obliged to constantly applying new fan constructions assuring lower noise by not lessened parameters of characteristics especially the efficiency. Enlarging its offer by a new axial fan WOO-63, in Gdańsk Assembly-Repairing Works, the decision was taken to make not only a fan with straigth blade but also the fan with swept blades and to investigate and compare their characteristics especially efficiency and noise. This interest was also result of searching of new fan construction assuring a reduced noise level.

2 Fan WOO-63 with straight blades

In the Gdańsk Assembly-Repairing Works (GZRM, Gdańsk), the new fan WOO-63 with straight blades was developed. This fan was also a main goal of the project broadening the fan offer of the works.

The basic assumption of the fan provided the external diameter of ϕ 630, the asynchronous electric motor of power 11 kW and n = 3000 rev/min. This fan was planned for volume flow of $V = 9.0$ m^3/s and pressure rise of $\Delta p = 1000$ Pa, and overall efficiency not lower than $\eta > 0.80$. Next the diameter ratio was assumed to be $D_w/D_z = 0.5$. By developing this fan the experience of calculating of the new series of axial fans for Malbork Fan Works was utilized [8, 13]. After performing the series of calculation by using the code based on the 1D theory according to Wallis [11] the choice of the fan is made which meets best the basic assumptions. So basing on these calculations the best fan rotor was chosen.

The fan rotor consists of ten blades of the NACA 65010 profiles family, whereas the stator consists of 11 non-profiled blades. The rotor blades of the WOO-63 fan were laid out by the method of arbitrary vortex flow based on the monograph of Wallis [11].

The calculation by this method was accomplished taking into consideration the reduction of the fan noise. In the literature the notion can be found that the fans laid out by the method of free vortex should give more silent fans because of the lower stream mixing behind the rotor, so thus the lower turbulent noise. However, in our case it was decided to make use of the arbitrary vortex method because the blades developed by this method have much smaller turning angle than in the free vortex method, so it is expected the stream mixing behind the rotor should be also a bit smaller.

The measurements of noise level, i.e. $L_{pA} = 113$ dB generated by the fan WOO-63 with straight blades shown that this fan can be classified to the second class of noisiness of fans [4], so more than 10 dB below the limits permissible for the fan with these volume flow rate and pressure rise.

3 Fan WOO-63 with swept blades

The one-dimensional aerodynamic calculations of fan with straight blades were the foundation for the calculations of rotor with swept blades.

Basing on the report by Wright and Simmons [16] and Fukano et al. [2] it was decided to incline the blade construction line forwards in its location plane, so the blade was chosen only with the sweep, i.e. λ <0 and without deflection, i.e. μ=0 so without inclining the blade in the circumferential direction. It is possible to choose the constant or varying sweep angle of the blade design line. In our case it was decided to choose the varying sweep angle along the blade. However from many possibilities for the shape of blade design line the logarithmic spiral was chosen, which normally has the constant angle α between the tangent to the spiral and radius vector at any point.

The angle difference $\Delta\Theta$ of logarithmic spiral between the internal and external rotor (blade) radii is given by following expression:

$$r_z = r_w \exp(k\Delta\Theta)\,, \tag{1}$$

where r_z and r_w are the external and internal radia of blade, whereas the coefficient k is a parameter determining the angle α between the tangent to the spiral and its radius vector according to the formula (2). When the value of k is constant than the angle α between the tangent and radius vector is also constant.

$$k = \cot\alpha\,. \tag{2}$$

Forcing the variation of parameter k it is also possible to force the variation of angle α, what is done later using the results of Wright and Simmons, [16].

Knowing the angle α between the tangent to the logarithmic spiral and radius vector it is possible to determine the sweep angle λ as

$$\lambda = \frac{\pi}{2} - \alpha\,. \tag{3}$$

If it is assumed that the blade construction provide only sweep i.e. $\lambda \neq 0$ and lack of deflection, i.e. $\mu = 0$, than the design line of the blade will lie in the plane situated at the stagger angle of the blade. The intersection of this plane with the casing of fan gives the ellipse with the following axes:

$$a = \frac{r_z}{\cos\xi} \qquad b = r_z \,. \tag{4}$$

It is also possible to calculate the ellipse angle ϕ_z, where the external radius of spiral cuts the ellipse:

$$\cos\varphi_z = \sqrt{\frac{B-1}{A-1}}\,, \tag{5}$$

where

$$A = \frac{1}{\cos^2\xi} \qquad B = \left(\frac{r_w}{r_z}\right)^2 \exp(2k\Delta\Theta)\,. \tag{6}$$

In this way determining the length of the blade design line:

$$L = \frac{\sqrt{1+k^2}}{k}\left(\frac{r_z}{\cos\xi} - r_w\right)\,. \tag{7}$$

It is easy to notice that the length of blade line, and thus also the length of blade, depends on the stagger angle of the blade in the rotor. Additionally, the casing length along the fan axis to cover the blading can be varying depended on the stagger angle. For the swept blade once manufactured the changed stagger angle will cause the change of the tip clearance. In our case the nominal stagger angle ξ of the swept blade is of the same value as for the straight blade at hub.

However Wright and Simmons [16], basing on the work of Fukano et al. [2], proposed the choice of the logarithmic spiral of the varying angle α between the tangent to the spiral and the radius vector, so with the varying parameter k:

$$k = f(\Theta)\,. \tag{8}$$

In the case considered in this work the linear increase of the angle α is assumed, i.e. from 30 to 45^oC, which should give the 6-8 dB reduction of the second harmonics of the fan noise [16].

The blade line, i.e. logarithmic spiral begins at the hub with sweep angle of $\lambda = 30^o$ and finishes at the top with the sweep angle $\lambda = 45^o$. Aerodynamic profile of blade is set perpendicular to the logarithmic spiral, Eq. (3). In such a way designed blade in its projection on the rotation plane is shown in Fig. 2.

It can be expected that the swept location of the blade which is firstly designed as a straight one changes the onflow condition, so the appropriate modification of the blade angles and its chord length are necessary. The blade profiles from the straight blade calculation should be modified, it refers specially the profile camber angle and incidence angle. These modifications are necessary because of

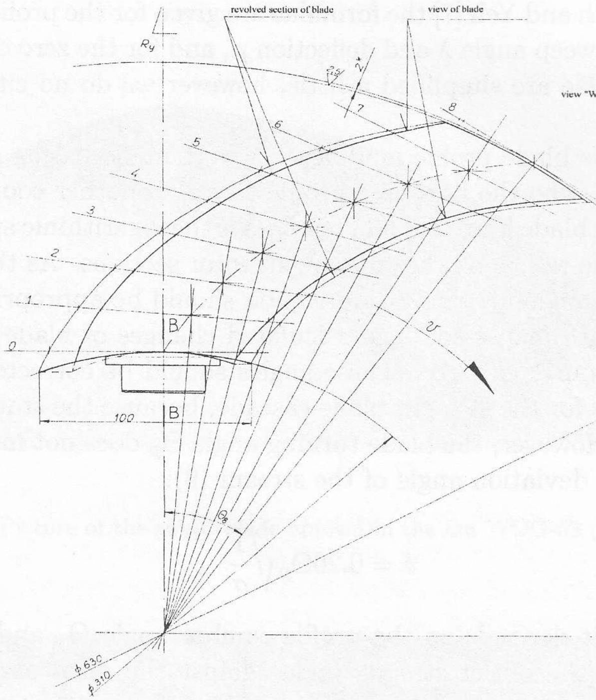

Figure 2. Design of swept blade (projection on the rotation plane of fan).

the swept blade line and their aim is to compensate the decrease of the pressure rise [7].

According to the method of Smith and Yeh [7] the profiles should be set in the new position and the new turning angles of the stream should be calculated by means of the projection method of the axisymmetric surface of the meridional flow on the surface perpendicular to the blade line. In the method of Smith and Yeh [7] the profile of the straight blade is initial state to design the swept blade and to receive the swept blade two procedures are proposed:

1. The profile of the straight blade should be displaced parallel (without turn) to the desired position r_i of the swept blade line and than the corrections caused by the projection on the plane perpendicular to the blade line can be calculated.

2. The profile of the blade should be displaced to desired position r_i , and with turn of sweep angle λ and next the correction calculated referring the projection of the profile on the axisymmetric surface.

In the work of Smith and Yeh [7] the formulae are given for the profile modification depending on the sweep angle λ and deflection μ, and for the zero deflection angle $\mu = 0$ these formulae are simplified a little, however we do no cite them in this paper.

In this work the blade profile modification were made basing on the work of Smith and Yeh [7], who the flow past profile treat in another coordinate system connected with the blade line, which in our case is the logarithmic spiral of varying angle relative to the radius on the subsequent rotor sections. As the consequence the profile camber angle for each blade section should be appropriately modified and the chord length increased. The calculated changes of blade camber angles are in the range from 1^oCto 2^oC. These angles should be corrected to bring the flow turning angles for the straight blade cascade, because the stator blading was left not changed. However, the blade turning angle Θ_p does not make much here, because the outlet deviation angle of the stream (9):

$$\delta = 0.26\Theta_p\sqrt{\frac{1}{\sigma}} \tag{9}$$

also increases, as it depends on the profile camber angle Θ_p and it contributes to the increase of the outlet stream angle against the prior assumption. The deviation angle δ was calculated by means of the three different ways and the results of calculations were approximately the same. The best result was achieved by decreasing the solidity σ as given in (10)

$$\sigma = \frac{s}{c}, \tag{10}$$

so by increasing the length of chord.

It gives good results for the section close to the tip of blade, but a little worse at the hub of blade. Finally, basing briefly described calculations the model of the swept blade is made and then their castings from the aluminium alloy AK64 were made, too.

In Fig. 3, the picture of the blade with forward sweep is shown. Furthermore, in Fig. 4 the picture of the axial fan WOO-63 with swept blades made in GZRM, Gdańsk, is shown.

4 Performance of the axial fan WOO-63 with straight and swept blades

The performance investigation of the fan WOO-63 with straight and swept blades were made at the fan stand in GZRM, Gdańsk. At this stand the common standard investigation of fans produced in these works are accomplished. The

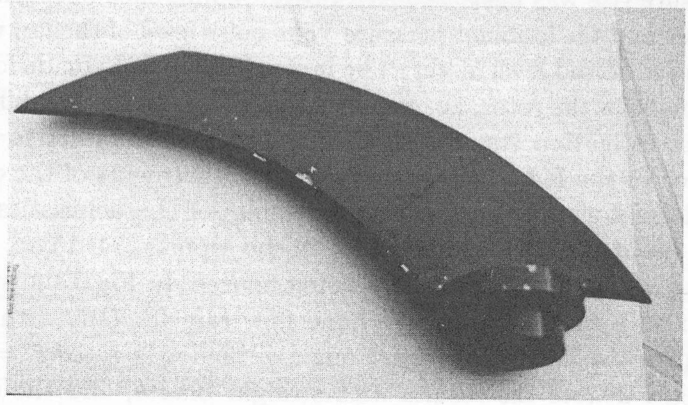

Figure 3. Picture of the swept blade applied in the fan WOO-63 (forward sweep).

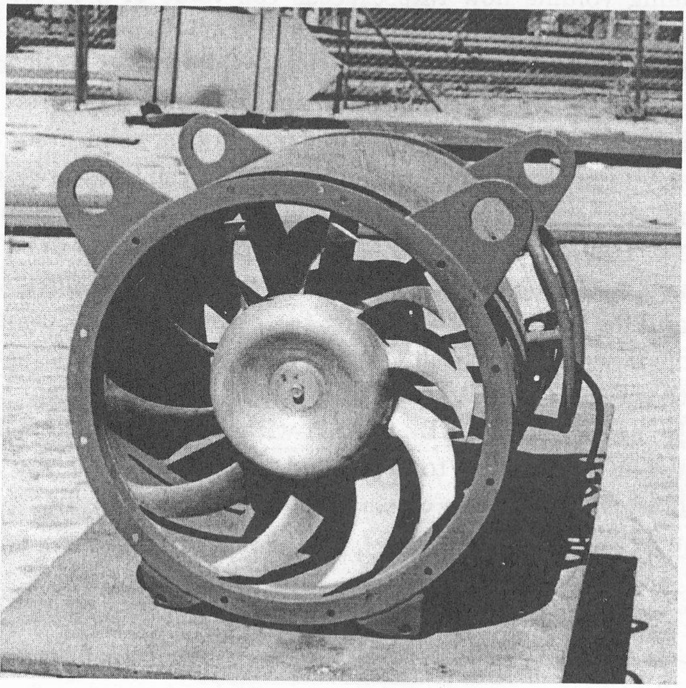

Figure 4. Picture of the axial fan WOO-63/S with swept blade (forward sweep).

volume flow rate was measured by means of the orifice at inlet to the fan channel, and the pressure rise was measured as a pressure difference between the pressure at the fan inlet and the ambient pressure. The noise level of the fan was measured by the integrated sound level meter. The investigations were made for two stagger angle of the blade in the rotor, i.e. $\xi = 61^o$Cand 56^oCand for five different orifices. So it is the investigation stand with with the pipe at the inlet to the fan. The power supplied to the fan was determined by measurements of the electric power of the electric motor. The measurements results of characteristics of fans with straight and swept blades were presented in the reports [14, 15].
Some of these results are shown in following figures. In Fig.5 the static pressure rise is shown as a function of the volume flow rate for fans with straight and swept blades for two different stagger angle of blades in rotor $\xi = 61^\circ$ and 56°. The black signs denote the results with straight blades, and the empty ones – with swept blades.

It is easy to see that the static pressure rise is actually almost the same for both types of blades and for both stagger angles. From the efficiency diagram, given in Fig. 6, it is to note that the efficiency is pretty high for considered fans and in prevailing volume flow rate exceeds the value of $\eta > 0.8$ and reaching even the value 0.9. Likewise in the case of efficiency measurement the difference between the both blade types are very small and they are enclosed in 2 percentage points, which actually lies in the range of the measurements error.

Next, in Fig. 7, the noise level measurement plots are shown for both fans and it can be clearly seen that the overall noise level of the swept blade fan is about 6 to 9 dB smaller then for the fan with straight blades and in principle for both stagger angles. The analysis of the presented plots allow to draw the following conclusion that the characteristics of both fans with straight and swept blades are very similar and for the stagger angle $\xi = 61^\circ$ both fulfill the design assumptions i.e. the volume flow rate $V = 9$ m^3/s and static pressure rise $\Delta p = 1000$ Pa.

On the other hand the noise generated by the fans with swept blades is much lower from the noise generated by the fan with straight blades. If the fan with straight blades can be classified to the second class of noisiness, then the reduction of noise of about 6 dB allow to classify the fan with swept blades to the fourth class of noisiness [4].

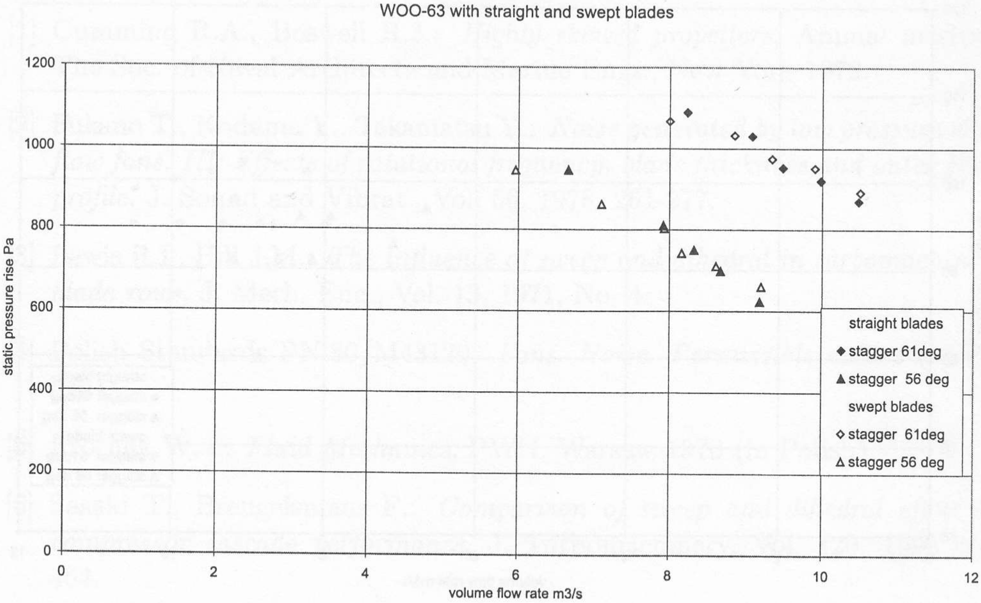

Figure 5. Static pressure rise of the fan WOO –63 with straight and swept blades.

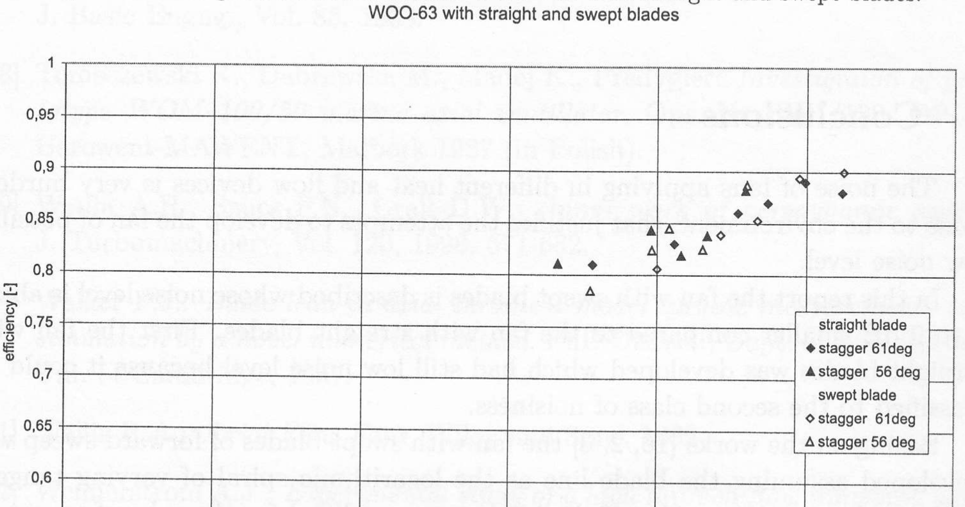

Figure 6. Efficiency of the fan WOO-63 with straight and swept blades.

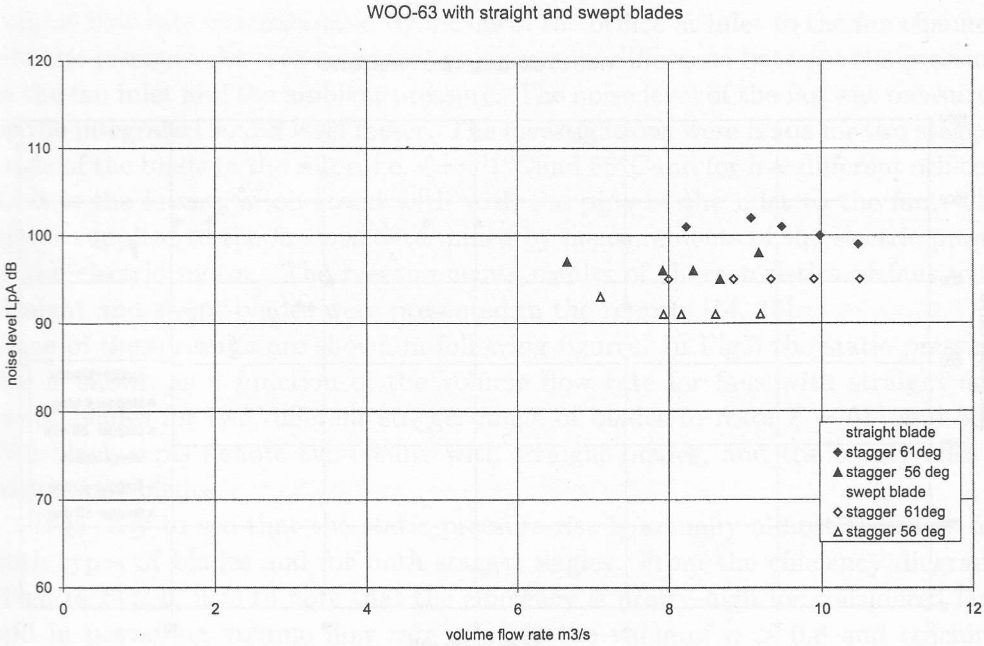

Figure 7. Noise level of the fan WOO-63 with straight and swept blades.

5 Conclusions

The noise of fans applying in different heat and flow devices is very burdensome to the environment, that justifies the attempts to develop the fan of possibly low noise level.

In this report the fan with swept blades is described whose noise level is about 6 to 9 dB smaller compared to the fan with straight blades. First the fan with straight blades was developed which had still low noise level because it could be classified to the second class of noisiness.

Basing on the works [16, 2, 3] the fan with swept blades of forward sweep was developed assuming the blade line as the logarithmic spiral of varying tangent angle, and next the profiles of the blade were modified for the sake of sweep regarding to the profile of the straight blade. The stator blading remained the same as in the fan with straight blades. The results of characteristics measurements certify that the fan with swept blades has much lower noisiness than the fan with straight blades, if the appropriate modification of profiles of straight blades aimed to receive the same performance of fan were made.

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