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STRUCTURE-BORNE NOISE GENERATED BY VACUUM CLEANER SUCTION UNITS

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Abstract

Noise emitted by a vacuum cleaner suction unit consists of airborne and structure-borne noise. The airborne noise is generated mainly by the turbo blower and the structure-borne noise is generated mainly by the driving electric motor. Structure-borne noise is an audible sound that is structural in origin, i.e., it begins as vibration. Basically, each substructure of a suction unit has one of the resonance frequencies and can affect the overall vibration behaviour. The normal mode of vibration of each part of the suction unit depends on its mechanical properties. The structure-borne noise depends on the suction unit design and on operating conditions. In this paper the effects of vibrations of the suction unit structure on the noise characteristics have been measured and analysed at the design and off-design operation. Measurement results have shown that contribution of structure-borne noise to the total sound pressure level becomes important at partial flow rates, especially when the rotating stall and surge in the turbo blower appear, and is relatively less important at higher flow rates and towards the free delivery. Among geometrical parameters, the stator of the turbo blower and electric motor, or metal shield if any, are main origins of the structure-borne noise. A vaned diffuser built-in the blower has the greatest effect on the structure-borne noise.

1. INTRODUCTION

A suction unit built into a vacuum cleaner for housekeeping applications consists of two main parts, a driving electric motor (EM) and a centrifugal blower (Fig. 1). The total emitted noise of the suction unit is generated partially by the blower and partially by the EM and consists of airborne and structure-borne (SB) origins. The airborne noise is generated mainly by the turbo blower and the SB noise is generated mainly by the driving EM. The contribution of the SB noise to the total sound pressure level (SPL) depends on the geometry of the EM and on the operating conditions (speed and load).

Among the geometrical parameters, the stator of the EM, and among operating conditions the appearance of rotating stalls and surge, are the most influential parameters for generation of the SB noise and to its contribution to the total SPL. The contribution of the SB noise to the total SPL also depends on the stator of the blower, i.e., the built-in vaned diffuser.

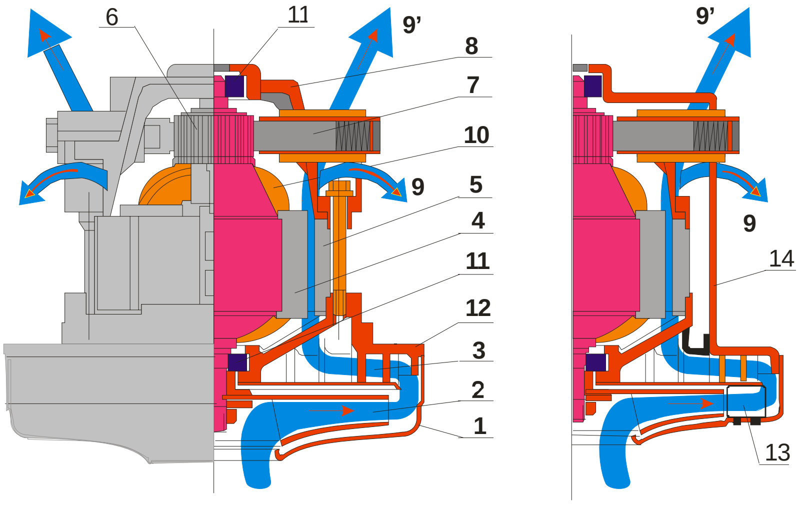

Figure 1. Single stage dry suction unit: *a*) without vaned diffuser and *b*) with vaned diffuser; 1-blower cowl, 2-rotor of the blower, 3-return passages, 4-stator of the EM, 5-rotor of the EM, 6-collector, 7-commutator brushes, 8-yoke B, 9- and 9'-air jets, 10-windings, 11-ball bearings, 12-yoke A, 13-diffuser vanes, and 14-cilindrical metal shield

Basically, each substructure of a suction unit (stator, rotor, yokes, shield, blower cowl etc.) has one of the resonance frequencies. The normal mode of vibration of each part of the suction unit depends on its mechanical properties. For the EM stator's packet, the mechanical properties depend on the magnetostriction and attraction forces, on the number of teeth and slots, on material and windings, on fastening of the stator packet in the housing etc. This is similar with modes of vibration of the blower.

The structural resonances or natural frequencies can easily be distinguished from the harmonic-order-related frequencies within the spectra by continuously changing the voltage supply or rotational speed and observing the local vibration maxims. When a discrete frequency (or broadband group of frequencies) is not changing with changing the rotational speed, then this is a constant natural or resonant frequency (mode of vibration) as part of SB noise, which theoretically does not depend on the excited forces. On the other hand, if a discrete frequency is changing with rotating speed, then this is a different harmonic of rotation and is not a result of structural resonances, [1, 2].

The noise spectrum of a suction unit is broadband in nature with superimposed discrete frequency tones. The discrete frequency tones are mainly produced by an interaction of the rotor blades of the blower with the inflow distortion and nearby stationary objects; by mechanical friction in the bearings and collector-commutator brushes and by periodical changes of magnetic flux in EM. It usually appears at the RF, blade passage frequency (BPF) and commutator brush frequency (CBF), and their higher harmonics. The broadband or turbulent noise is mainly produced by laminar and turbulent boundary layer vortex sheddings, by blower blade interaction with the blade tip clearance vortices and blade stall and surge phenomena. Among them the surge phenomena is the most important one, and have a strong effect on the SB noise of the suction unit as whole [3-5].

Total emitted noise is a sum of the discrete frequency tones and broadband turbulent noise. Since the discrete frequency tones theoretically do not depend on the load, and the broadband turbulent noise increases at off-design operation, the total noise level usually has its minimum at the best efficiency point (BEP). The vaned diffuser, which is sometimes built into the blower, has an important effect on the total emitted noise and its spectra. Therefore, in this paper the contribution of the SB noise to the total SPL is measured and analysed at different operating conditions (speed and load) and at different geometries of the suction units observed, i.e., with and without a vaned diffuser.

2. TEST PROCEDURE

Two different types of suction units were used in the experiments: four having blowers without vaned diffusers and four having blowers with vaned diffusers. Vibrations were measured by an accelerometer, B&K, Type 4371, mounted on different parts of the suction unit. The SPL was measured by a half-inch microphone, B&K, Type 4155, placed at a distance of 1 m, in the vicinity of the suction unit and perpendicular to the brushes axis. Both measurement results have been analysed by a two-channel B&K FFT analyser, Type 2032. Vibration and noise characteristics of the suction units were measured simultaneously on a special test plenum built according to the IEC 312 standard and placed into an anechoic chamber with a volume of 25 m^3. The blower backpressure was varied by throttling of the inlet opening on the test plenum using adjustable orifices according to the cited standards, with ten different diameters from 0 to 50 mm (or ϕ0, ϕ6.5, ϕ10, ϕ13, ϕ16, ϕ19, ϕ23, ϕ30, ϕ40 and ϕ50 mm), [5].

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Contribution of Noise of the Electric Motor (EM) to the Total SPL

The driving EM causes mainly SB noise and only a small part of aerodynamically generated noise. The contribution of noise of the EM to the total SPL was determined by a separate noise measurement of the complete suction unit and the same suction unit with a dismantled rotor of the blower and its cowl, i.e., by the EM alone, [4].

In Fig. 2 noise spectra of the suction unit without vaned diffuser for the complete suction unit (upper spectra) and without the rotor of the blower are depicted, i.e., with the EM alone (lower spectra) at rotational speeds corresponding to the constant voltage supply (230 V) and three characteristic orifice diameters: ϕ0 mm (zero flow rate), ϕ19 mm (BEP) and ϕ50 mm (free delivery). We can see that the noise generated by the EM depends on the operating point, i.e., on the load and rotational speed. The noise spectra of the EM alone are characteristically narrow-band (lined spectra) with many discrete frequency tones, which are in the form of a harmonic series with the RF and are thus discrete frequency in origin. Among them, the first four harmonics of the RF and commutator brush frequency (CBF) are especially pronounced. These tones are excited by a harmonically-acting vibration caused by unbalanced rotating masses, friction in commutator brushes and bearings. In addition, the noise spectra of the EM also contain discrete frequency tones of SB origin, which are caused by modes of vibration (mostly of the stator packet of the EM, and metal shield if any). The EM also generates a broadband noise but usually at a much lower level than the discrete frequency tones. Differences between the discrete frequency tones and the broadband noise are up to 15 dB(A) and more (Fig. 2).

When the rotor of the blower is mounted on the EM shaft, additional discrete frequency tones at the BPF and its higher harmonics are generated. In addition, a high level of broadband noise is generated. Fig. 2 shows that the total SPL of the complete suction unit with a running blower is much higher than those generated by the EM alone; differences are up to 13 dB(A) at an orifice of ϕ0 mm, up to 11 dB(A) at an orifice of ϕ19 mm, and up to 17 dB(A) at an orifice of ϕ50 mm. Similar results were obtained by Brungart et al. [6]. These differences are so great that we can say that the effect of the EM to the total SPL is rather small. However, detailed analyses of noise and vibration spectra measured on the complete suction unit have shown that their effect to the total SPL cannot be entirely neglected. For this reason, simultaneous measurement of noise and vibrations were performed on the same suction unit.

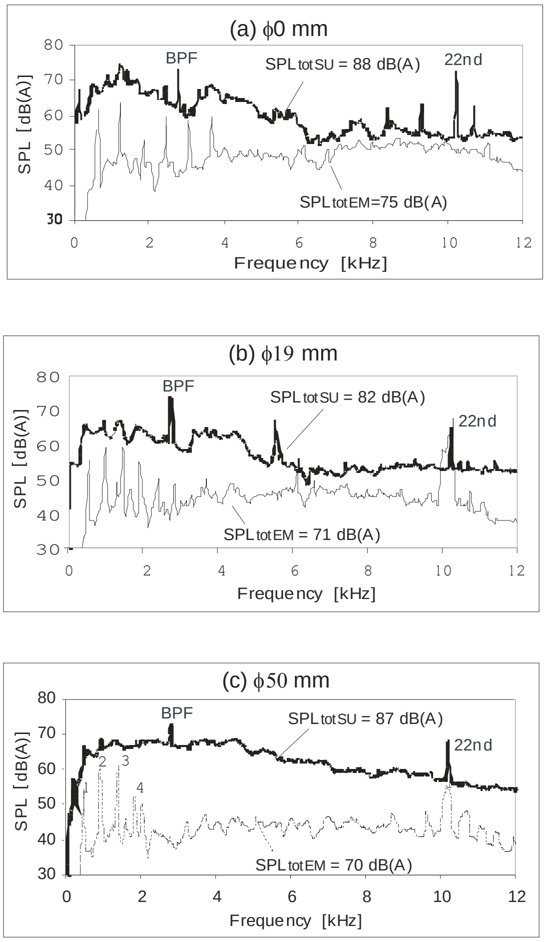

Figure 2. Noise spectra of complete suction unit without vaned diffuser (thick curve) and with dismantled rotor of the blower (thin curve) at constant voltage supply (230 V) and different flow regimes: *a*) at zero flow rate (orifice ϕ0 mm), *b*) at BEP (orifice ϕ19 mm) and *c*) at free delivery (orifice ϕ50 mm); SPL_{totSU}-total sound pressure level of the suction unit, SPL_{totEM}-total sound pressure level of the EM

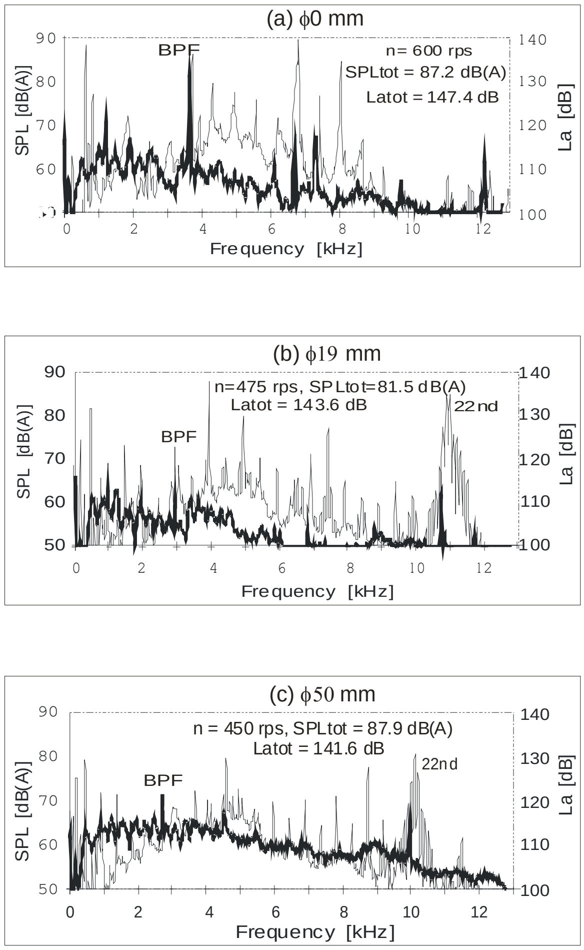

Figure 3. Comparison between noise spectra (thick curve) and vibration spectra (thin curve) of suction unit without vaned diffuser at constant voltage supply (230 V) and different flow regimes: *a*) at zero flow rate (orifice ϕ0 mm), *b*) at BEP (orifice ϕ19 mm) and *c*) at free delivery (orifice ϕ50 mm); *n*–rotational speed, BPF–blade passage frequency, SPL_{tot}–total spound pressure level, L_{atot}–total level of vibration velocity

The vibrations were measured by an accelerometer fastened to the stator of the EM (in a radial direction), while the noise was measured by a microphone placed at a distance of 1 m from the suction unit. Fig. 3 shows simultaneously measured noise spectra (thick curves) and vibration spectra (thin curves) for suction unit without vaned diffuser at constant voltage supply (230 V) and three different orifices (ϕ0 mm, ϕ19 mm and ϕ50 mm) for comparison. We can see typically narrow-band vibration spectra with many pronounced discrete frequency tones within entire frequency range. Among them, the peaks corresponding to the RF, BPF and CBF, and their higher harmonics are the most pronounced. Additionally, a broadband peak between 4 and 6 kHz is especially pronounced. All peaks previously listed are a result of the common action of the mechanically, electromagnetically and aerodynamically excited forces, [6-8]. Among these of mechanical origin the most important are those excited by the unbalanced rotating masses of the rotors of the EM and the blower, as well as bearings and commutator-brush friction. Among these of aerodynamic origin the most important are those excited by the BPF, rotating stall and surge phenomenon. The level of these vibrations depends, amongst other factors, on the modes of vibration. The modes of vibration depend on structural design of the suction unit, or form, rigidity, thickness, mass and material used. The highest values of vibrations appear at the partial flow rate, when the rotating stalls and surge phenomena appear (Fig. 3).

The pronounced peak in vibration spectra, between 4 and 6 kHz (Fig. 3), and pronounced discrete frequency tones within this peak are not in correlation with the RF, therefore they are SB in origin due to resonances. These peaks are not seen in noise spectra of the EM alone (suction unit without the rotor of the blower) in Fig. 2 (thin curves). This means that they are a result of excited forces caused by the processes within the blower, which are manifesting through the suction unit (EM) structure in form of vibrations of the structure.

A cursory glance at the spectra in Figs. 3a to c shows that most of the peaks in the vibration spectra do not coincide with the peaks of the noise spectra. However, a detailed analysis of the peaks in vibration spectra at the low frequency below BPF has shown that these peaks fully coincide with the corresponding peaks in noise spectra for the EM alone (Fig. 42), although there are some new peaks caused by the operation of the blower. These peaks are not seen in the noise spectra of the complete suction unit (with rotor of the blower) because they are mostly masked by broadband noise. The broadband turbulent noise, which is mostly of aerodynamic origin caused within the blower and EM, and the jets flow due to the exiting air flow on the EM side, more or less overlaps the discrete frequency tones of the RF and BPF as well as SB noise until it fully dominates, especially at the free delivery (Fig. 2c). As a result of this, the discrete peaks in noise spectra (thick curves in Figs. 2 and 3) are mostly masked by the broadband noise, but they are evidently reflected in pronounced broadband noise peaks in corresponding frequency region.

3.2. Structure-Borne Noise at Different Operating Conditions

Fig. 4 shows the noise spectra of a suction unit without vaned diffuser at three different rotational speeds (196, 296 and 460 rps), and ten different loads (orifice diameters $\phi0$, $\phi6.5$, $\phi10$, and through the series to $\phi50$ mm) as a parameter, and Fig. 5 shows noise spectra of the suction unit without vaned diffuser at three different loads (orifices $\phi0$, $\phi19$ and $\phi50$ mm) and four different rotational speeds (200, 300, 375 and 450 rps) as parameter for comparison.

Similarly, Fig. 6 shows noise spectra of a suction unit with a vaned diffuser at three different rotational speeds (205, 285 and 450 rps), and ten different loads (orifices $\phi0$, $\phi6.5$, $\phi10$, and through the series to $\phi50$ mm) as parameter, and Fig. 7 shows noise spectra of the suction unit with a vaned diffuser at three different loads (orifices $\phi0$, $\phi16$ and $\phi50$ mm) and four different rotational speeds (200, 285, 350 and 420 rps) as parameter for comparison. Figs. 5a and 7a show noise spectra at an orifice of $\phi0$ mm (similar noise spectra are obtained at orifices of $\phi6.5$ mm and $\phi10$ mm), Figs. 5b and 7b show spectra for orifices of $\phi19$ mm and $\phi16$ mm, respectively (similar noise spectra are at orifices of $\phi16$ or $\phi19$ mm and $\phi13$ mm), and Figs. 5c and 7c show the same for an orifice of $\phi50$ mm (similar spectra are at orifices of $\phi40$ and $\phi30$ mm).

From Figs. 4 to 7 we can see that all spectra consist of broadband noise with pronounced discrete frequency tones. The pronounced discrete frequencies tones are at the BPF and its higher harmonics, and two less-pronounced broadband peaks are at the low frequency band, one between 500 and 2,500 Hz, and the other between 3,000 and 4,500 Hz. These two pronounced broadband peaks, having more pronounced discrete frequency peaks, are SB in origin due to structural resonances. The measurement results have shown that, at the constant voltage supply (230 V) and suction units without vaned diffuser, the pronounced peaks of structural resonances appear at discrete frequencies 700, 914, 944, 1,335, 2085, 3609 and 3820 Hz for a suction unit without vaned diffuser, and at discrete frequencies 515, 600, 867, 960, 1,171, 1,875, 2,367 and 2,460 Hz within the first broadband peak, and at 4,289, 5,484 and 6,890 Hz within the second broadband peak for suction units with a vaned diffuser.

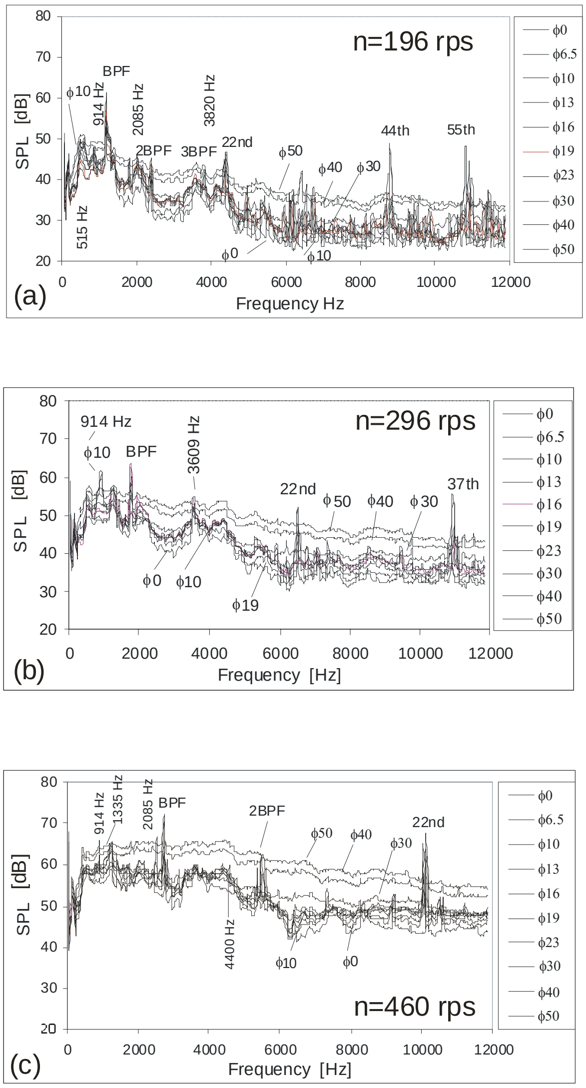

Figure 4. Noise spectra of suction unit without vaned diffuser at three rotational speeds (n = 196, 296 and 420 rps) and ten different flow regimes (orifice diameter ϕ0, ϕ6.5, ϕ10, …. to ϕ50 mm)

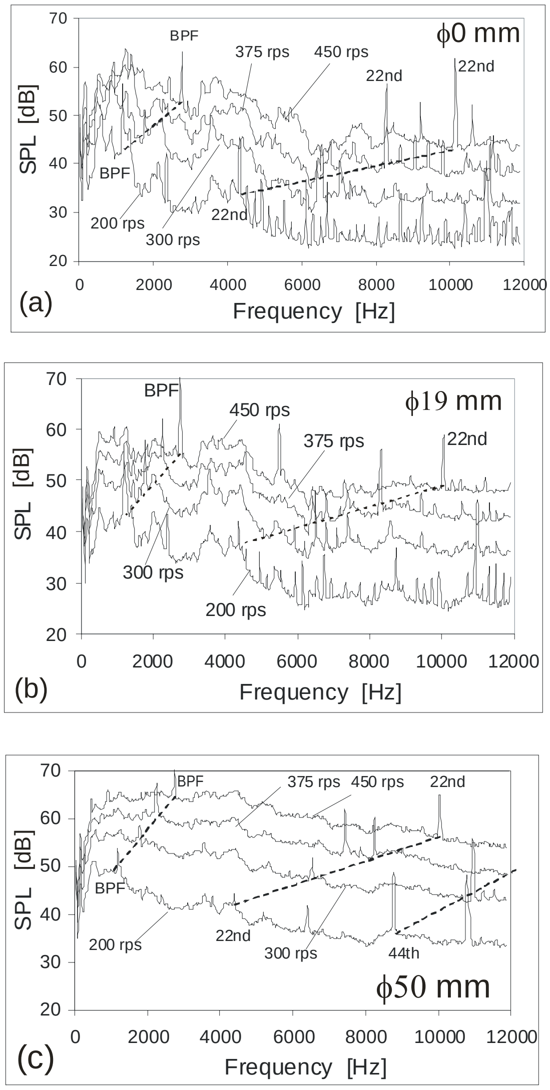

Figure 5. Noise spectra of suction unit without vaned diffuser at four rotational speeds (n = 200, 300, 375 and 450 rps) and three different flow regimes: *a*) at zero flow rate (orifice ϕ0 mm), *b*) at BEP (orifice ϕ19 mm) and *c*) at free delivery (orifice ϕ50 mm)

We must distinguish between contribution of the SB noise to the total SPL at the suction unit without and with a vaned diffuser. For the suction unit without a vaned diffuser, the SB noise at the low frequency range is prevailing at all rotational speeds when the flow rate is small enough, whereas at higher flow rates and sufficiently high rotational speeds, the broadband turbulent noise of aerodynamic origin prevails within the entire frequency range. This is a result of the fact that the magnitude of the aerodynamically generated broadband (turbulent) noise increases with rotational speed faster than the SB noise, [3]. The increase in flow rate causes an increase in aerodynamic noise due to higher flow velocity and greater effect of the laminar and turbulent boundary layer vortex shedding, as well as due to the stronger effect of the jet flows from the EM openings (Fig. 1). Turbulent noise of aerodynamic origin generated in this way increases steadily with flow rate and gradually overlaps the SB noise (pronounced at the low frequencies) as well as the noise at the RF and BPF, and their higher harmonics. At higher rotational speeds (above 350 rps) and for higher flow rates (above an orifice diameter of ϕ40 mm), the broadband turbulent noise of aerodynamic origin prevails within the entire frequency range and overlaps the SB noise at the low frequency range and almost overlaps even all noise at the BPF and its higher harmonics (Figs. 4c and 5c). This means that the total SPL is determined mostly by the SB noise at lower flow rates and lower rotational speeds, as well as by the aerodynamically generated noise at higher flow rates and higher rotational speeds.

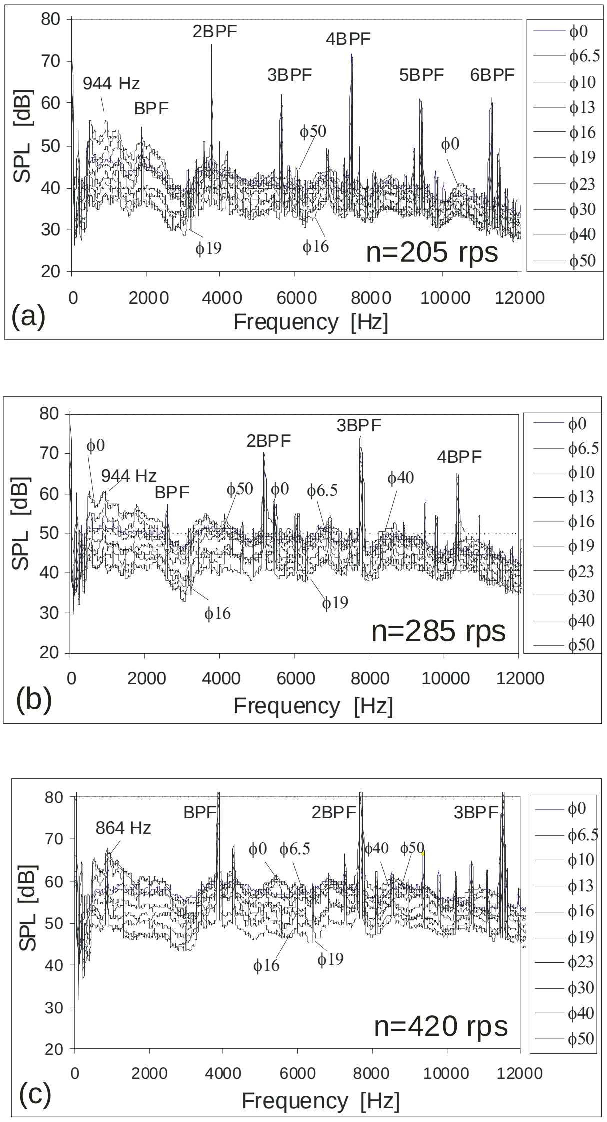

Figure 6. Noise spectra of suction unit with a vaned diffuser at three rotational speeds (n = 205, 285 and 420 rps) and ten different flow regimes (orifice diameter ϕ0, ϕ6.5, ϕ10, ….to ϕ50 mm); BPF – blade passage frequency

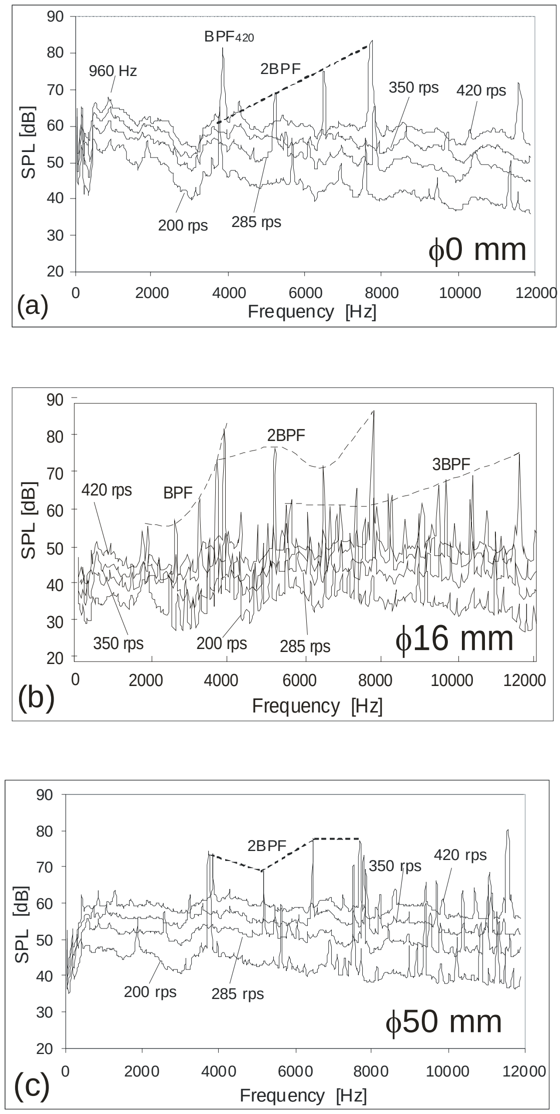

Figure 7. Noise spectra of suction unit with a vaned diffuser at four rotational speeds (n=200, 285, 350 and 420 rps) and three different flow regimes: *a*) at zero flow rate (orifice ϕ0 mm), *b*) at BEP (orifice ϕ16 mm) and *c*) at free delivery (orifice ϕ50 mm); BPF–blade passage frequency

For the suction units with a blower having a vaned diffuser, the SB noise is of the same order of magnitude as those for the suction units without a vaned diffuser (compare Fig. 6 and Fig. 4). However, due to the much higher level of discrete frequency noise at the BPF and its higher harmonics (differences are up to 15 and 20 dB), its effect to the total SPL is much smaller.

4. CONCLUSIONS

The total emitted noise of a suction unit is generated partially by the blower and partially by the driving electric motor (EM) and consists of airborne and structure-borne (SB) origins. The airborne noise is generated mainly by the turbo blower and the SB noise is generated mainly by the EM. The SB noise depends on the suction unit geometry; first of all, on the stator of the EM and the stator of the blower, or built-in vaned diffuser, and on operating conditions (speed and load). For the suction unit having a blower without vaned diffuser, the SB noise is pronounced at the low frequency range and usually determines the total SPL at partial flow rates and lower rotational speeds, whereas at higher flow rates and higher rotational speeds the aerodynamically generated broadband (turbulent) noise increases so much that it overlap the SB noise. For the suction unit having a blower with built-in a vaned diffuser, the SB noise, although being of the same order of magnitude as those at the suction unit without a vaned diffuser, is of lesser importance due to the much higher discrete frequency noise at the BPF and its higher harmonics.

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