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Identification of noise sources in centrifugal blower with acoustic camera

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A suction unit represents the main noise source in a vacuum cleaner. Noise generated by the suction unit has aerodynamic, mechanical and electromagnetic origins. Noise emitted by a suction unit consists of airborne and structure-borne noise. The contribution of the individual noise source to the total noise level depends on the geometry of the suction unit and operating conditions (rotational speed and load). The operating condition of a suction unit depends on the amount of dust in a dust bag and is constantly changing during operation. In order to reduce noise of suction unit in a broad range of operating conditions, an identification of noise sources needs to be performed. Identification of most important noise sources on the centrifugal blower was performed with an acoustic camera at the design and off-design operation conditions. From the analyses we can conclude that the rotational noise usually prevails at the design point of operation, and that the non-rotational noise prevails at off-design operation. The main source of noise within a suction unit can be attributed to the aerodynamically generated noise, at the design as well as at off-design operation.

1. Introduction

Inherit problem of a suction unit is, that generated pressure rise Δp strongly depends on the flow rate Q (red curves in Fig.1). On the other hand, flow rate depends on the resistance characteristic of the vacuum cleaner into which suction unit is integrated and on the pressure rise, generated by the suction unit. Operating point is thus intersection of suction unit characteristic with resistance characteristic of the vacuum cleaner.
In the design phase of a suction unit, its geometry and its rotational speed (n_{des}) are calculated for desired flow rate (Q_{des}), desired pressure rise (Δp_{des}), and for specific vacuum cleaner. If the suction unit operates under these conditions, the best efficiency point (BEP) is achieved, Fig.1. However, the resistance characteristic of the vacuum cleaner depends on the amount of dust particles in the dust bag. During operation of the suction unit, the dust particles are gathering in the dust bag causing a flow resistance and shifting the operating point to lower flow rates and to higher pressure rise. The suction unit built into a vacuum cleaner operates from free delivery (Q_{max}) to a minimum flow rate (Q_{min}).

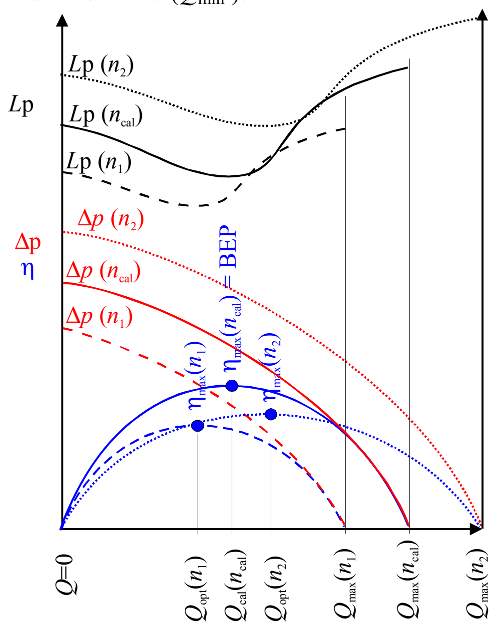

Fig. 1. Typical characteristics of suction unit

Due to the leakage of the vacuum cleaner housing and the chock line caused by the system characteristic, a suction unit built into the vacuum cleaner usually operates within a range of approximately 110–15% of the designed flow rate (Q_{des}). This means that the operation point of the suction unit relatively quickly goes over the BEP to lower flow rates and so to lower efficiencies. By reducing the airflow, temperature of the cooling air increases. The temperature of the electric motor starts to increase rapidly. Longer operation of the suction unit under these conditions is not recommended. Further more, vacuum cleaners are usually equipped with electronic control for rotational speed of suction unit, which significantly affects its characteristic. Three characteristics of typical suction unit are depicted in Fig.1 for different rotational speeds $n_1 < n_{des}$, n_{des} and $n_2 > n_{des}$.
Noise generated by a suction unit consists of noise generated by the blower and by the electric motor. Suction unit noise has aerodynamic, mechanical and electromagnetic origins. The spectrum of the emitted noise is broadband with pronounced discrete frequency tones, which have rotational and non-rotational components [1]. Portions of the rotational and non-rotational noise components depend on the suction unit geometry and on operating conditions. The operating point of the suction unit working in a vacuum cleaner is constantly changing; therefore, the noise generating mechanisms, and consequently the total level of noise and its spectra, are also changing.

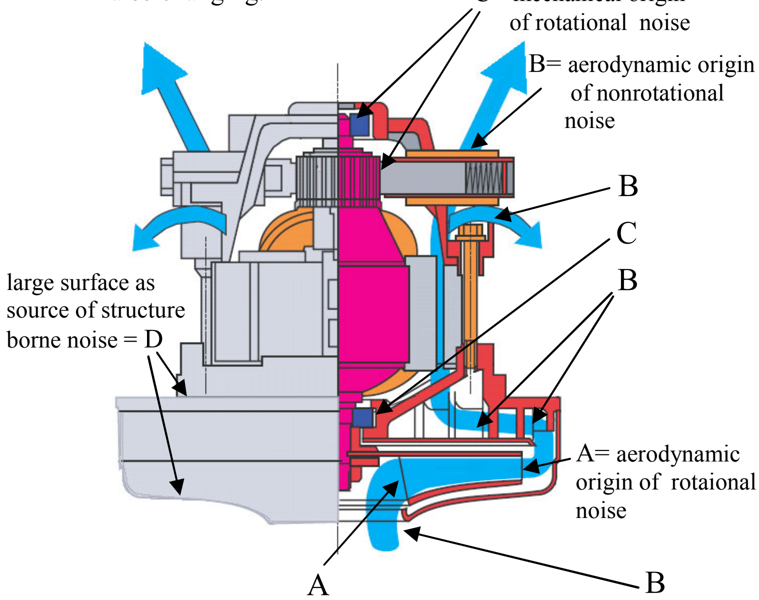

Fig. 2 Suction unit with depicted airflow

Noise can be classified according to its origin:
1. Aerodynamically generated noise
   - Rotational aerodynamic noise
   - Non-rotational aerodynamic noise
2. Mechanically generated noise
   - Rotational mechanical noise
   - Non-rotational mechanical noise
3. Structure-borne noise
4. Electro-magnetically generated noise

2. Aerodynamically generated noise

2.1. Rotational aerodynamic noise

Rotational noise of aerodynamic origin at the design point of operation (n_{des}, Q_{des}, Δp_{des}) is the result of pressure fluctuations caused by periodic fluid forces. Thrust and drag forces are induced on the blades as they move through the air. Rotational noise is also generated by impulsive interaction of the rotor blades with the inflow distortion and nearby stationary obstacles, such as the diffuser vanes and return passages (A in Fig. 2).

Rotational noise of aerodynamic origin at off-design operation and at constant rotational speed is theoretically equal to that at the design point of operation. But in reality, the rotational noise can be changed due to changing both the steady and unsteady loading effects, which are characteristic for the off-design operation [1].

2.2. Non-rotational aerodynamic noise

Randomly excited forces generate the non-rotational noise of aerodynamic origin, at the design and off-design point of operation. These forces are induced by the non-uniform flow fields, by turbulence and by interaction of the turbulent flow with the rigid structure along the flow through the blower and the electric motor. They are caused by widening or narrowing and banding of the flow passages, by asymmetries of the flow in the blower intake opening, by flow hitting and declination on the flow obstruction such as rotor blades, diffuser vanes, return passages, etc., with accompanying vortices. The non-rotational noise depends on the flow velocity, design, dimensions and roughness of the passages within the blower and the electric motor, [1]. Spatial origins of non-rotational noise are marked with B in Fig. 2.

At higher flow rates, towards free delivery ($Q>>Q_{des}$) aerodynamic non-rotational turbulent noise is generated due to higher flow velocities and incidence declination of the flow on the suction side of the rotor blade. Additionally, the emitted noise also increases due to the blade interaction with the tip clearance vortices and jet noise at the outlet openings of the electric motor. The tip clearance vortices are a result of a pressure difference between the pressure and suction sides of the rotor blade causing re-circulation flow in the annular gap between tip diameter of the rotor and diffuser.

At lower flow rates ($Q<Q_{des}$), the non-rotational aerodynamically generated noise is caused by vortices, flow declination and especially due to the onset of the rotating stall and surge phenomena. When the flow rate is further reduced (Q=> 0), in some cases, a surge point can occur. When the blower is "surging", the fluid starts flowing back from the discharge into the blower. The surge is connected with intensive pressure pulsation and fluctuation of the airflow. It is also a sign of instability in blower operation. The pressure pulsation causes deterioration of the suction unit performances and a great increase in vibration and resulting noise.

The non-rotational aerodynamic noise generated by turbulent flow is broadband in nature with few maxima in minima in spectrum. The non-rotational noise by rotating stall and surge is broadband in nature, with one or more peaks, which do not correlate with the integer number of the rotational frequency [1].

3. Mechanically generated noise

3.1 Rotational noise of mechanical origin

Rotational noise of mechanical origin is generated by:

1. vibrations caused by unbalanced rotating masses.
2. mechanical friction of the brushes over the collector,
3. rolling of balls in bearings.

The magnitude of the mechanical noise caused by unbalanced rotating masses depends on the rotational speed and degree of balancing of the rotating masses (rotors of the blower and the electric motor), and appears at the rotational frequency and its higher harmonics.

The commutator brush noise appears at the frequency that can be obtained by multiplication of the rotational speed and the number of collector segments.

The ball bearings generate noise with discrete frequencies corresponding to the rotating frequency. The magnitude of the ball bearing noise depends on the speed of rotation and their manufacturing perfections, alignment, wear and damage.

Spatial origin of rotational mechanical noise is therefore within the electric motor. Rotational mechanical noise has narrow band characteristics. Its noise spectrum consists of many discrete frequencies correlated to rotational frequency. Amplitude of individual discrete frequency in noise spectrum depends on

1. rotational speed,
2. quality of balancing the rotor
3. type of bearings and
4. construction of the commutator brush system.

At off-design operation, the rotational noise of mechanical origin has the same origins as at the design point of operation.

3.2 Non-rotational noise of mechanical origin

Origins of the non-rotational mechanical noise are steady and randomly excited internal forces. At design and off-design operation, the origins of non-rotational noise are the same, but magnitudes are different. At partial flow rates, the non-rotational noise of mechanical origin is intensified due to higher rotation speed and due to the onset of the rotating stall and surge phenomena. The surge phenomenon causes intensive fluctuation of the airflow and additional excitation forces with an increase in vibration. Increasing the rotational speed causes more intensive slipping of the brushes and consequently higher noise; although after a certain amount of operating time the formation of a patina of cooper oxide or a film of graphite dust and water on the collector can even reduce noise [1].

4. Structure born noise

Noise generated within the suction unit is transmitted to the surrounding air partially through the airflow openings and partially through the vibrating structure. Total noise level therefore depends on the airflow velocity, geometry of the openings and on the vibration of the suction unit structure surface. Noise generated by the vibration of the suction unit structure surface will be discussed as a structure-borne noise.

A structure-borne noise is a result of common action of the aerodynamically, mechanically and electro magnetically excited forces. A structure borne noise depends on the design, mass, rigidity and damping of the suction unit elements. The magnitude of vibrations depends on

- mechanical vibration characteristics,
- magnitude of the exciting force,
- difference between the frequency of the exciting force and the natural frequency
- damping conditions within the motor and the blower.

If the frequency of the exciting force is close to any of the natural frequencies of the motor and/or the blower, then resonance occurs resulting in steep increases in vibrations and noise. Structural resonance can easily be excited by the flow.

The structure-borne noise combines to produce a spectrum characterized by broadband noise and discrete frequency tones. These discrete frequency tones are not in correlation with the rotational frequency but with the modes of vibration; therefore they are non-rotational in nature.

5. Noise sources visualization

There are many methods available for noise source visualization; near-field acoustic holography, near-field sound pressure mapping, velocity mapping, sound intensity vectoring, sound intensity mapping, beamforming and others [2]. In majority they are limited by inherit Fourier transformations by using Fourier-windows and averaging wave numbers. These limitations can be overcome by working in time domain. Therefore, we used the most basic algorithm for mapping in the space-time domain by following equation:

$$\hat{f}(\mathbf{x}_j,t)=\frac{1}{M}\sum_{i=1}^{M} w_i f_i(\mathbf{x}_j,(t-\Delta_i)) \qquad (1)$$

This equation is long known from Delay-and-Sum beamforming and is the oldest and simplest array signal-processing algorithm [3].

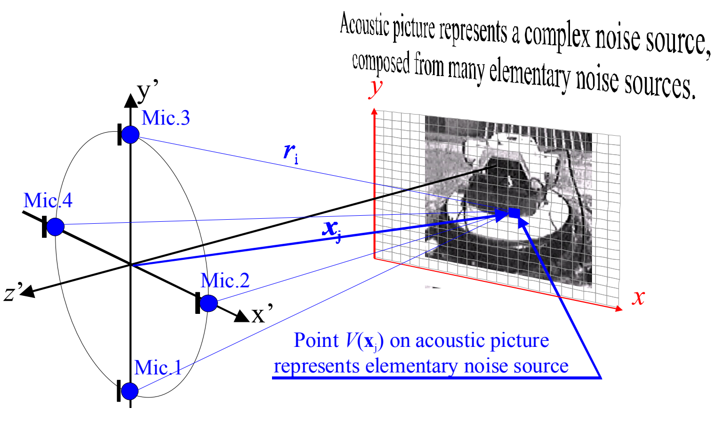

Fig. 3. Acoustic setup

Sound, generated by an elementary source (depicted with blue square $V(\mathbf{x}_j)$ in Fig.3) travels along vector $\mathbf{r}_{i,j}$ to each microphone on the microphone array. Lengths $|\mathbf{r}_{i,j}|$ of vectors from the elementary source to individual microphones differ. Therefore time delay $\Delta_{i,j}$ is inherited into signals from the individual elementary source. If the microphone array geometry is given and the distance from array center to noise source virtual plain is given, then vectors $\mathbf{r}_{i,j}$ with related time delays $\Delta_{i,j}$ can be calculated. If signals from individual microphones are accordingly delayed and summed, a new signal $f(\mathbf{x},t)$ is obtained. This is a signal of noise coming from elementary noise source $V(\mathbf{x}_j)$ to the reference microphone of the array. If elementary noise source does not generate noise, an average value from all signals will converge to zero value. This occurs only if microphone number is sufficient. Signal $f(\mathbf{x},t)$ is calculated for each point in an acoustic picture. By calculating its effective value $p_{eff}(\mathbf{x},t)$ according to equation,

$$p_{eff}(x)\approx p_{eff}(\mathbf{x},n)=\sqrt{\frac{1}{n}\sum_{k=0}^{n-1}\hat{f}^2(\mathbf{x},t_k)} \qquad (2)$$

a RMS value of noise signal $f(\mathbf{x},t)$ coming from elementary noise source is obtained. Effective value $p_{eff}(\mathbf{x},t)$ is then used for coloring the acoustic picture. Elementary noise sources on the virtual source plane with high values are colored red. Elementary noise sources with lower $p_{eff}(\mathbf{x},t)$ values are colored blue which fades to transparent. Superposition of video and acoustic picture gives an exact location of the elementary noise source, which generates the highest level of noise in given frequency range.

6. Measurement procedure and results

In order to incorporate wide range of operating conditions into analysis, suction unit without vaned diffuser was measured under different operating conditions:

1. delivering maximum flow at minimum pressure raise, (Q_{max}, Δp_{min}),
2. working under conditions for which it was designed for (Q_{des}, Δp_{des}),
3. achieving maximum pressure with minimum flow, (Q_{min} Δp_{max}).

Under each operating condition, the suction unit was tested for different voltages supply. That is for different rotational speeds; (230 V, 200 V, 170 V, 140 V, 110 V, 80 V, 50 V, 20 V).

Results are presented in Figs. 4 and 5. In Fig. 4 noise spectra of suction unit delivering maximal flow with practically no pressure raise are presented. In Fig. 5 noise spectra of suction unit achieving maximum pressure raise and a minimum flow rate are presented. A higher voltage supply results in higher rotational speed and consequently in a higher noise spectrum.

Amplitude of broadband noise, generated by the suction unit, is correlated with the rotational speed. Discrete frequencies are also correlated with rotational speed. However, the amplitude of individual discrete frequencies is hard to predict. In some cases, the amplitude of individual frequency from the same noise origin is higher at lower rotational speed than at higher rotational speed. By comparing spectra of suction unit driven with 50 V (black spectrum) and with 80 V (dark blue spectrum) and working under different operating conditions, we can observe how broadband aerodynamic noise and structure born noise covers discrete frequencies.

An increase of the rotational speed has different effects on different parts of the spectra. This difference is a result of different partial contribution of the aerodynamical, mechanical, electromechanical, and structure borne noise. The magnitude of the broadband turbulent noise of aerodynamic origin increases, by increasing the rotational speed, faster than the magnitude of the structure-borne noise. The aerodynamically generated turbulent noise increases with flow velocity, while the structure-borne noise increases with vibration velocity of the structure, (Fig. 6).

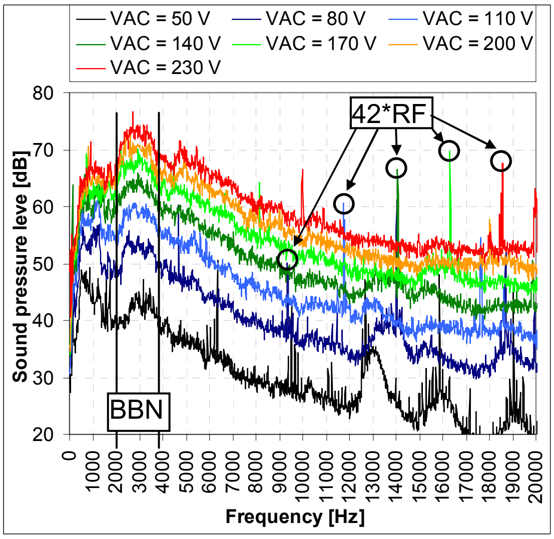

Fig. 4. Noise spectra of suction unit delivering maximum flow with minimum pressure rise, (Q_{max}, Δp_{min})

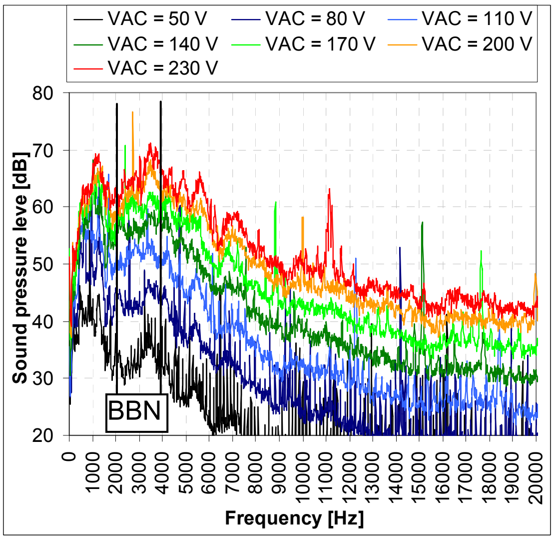

Fig. 5. Noise spectra of suction unit delivering partial flow rate with maximum pressure rise, (Q_{min}, Δp_{max})

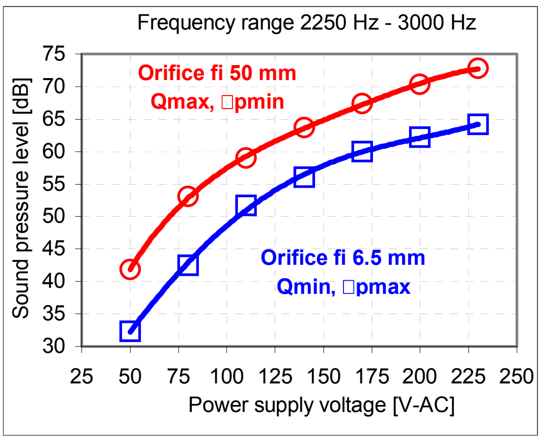

Fig. 6. Noise level as a function of voltage supply for maximum and minimum flow rate

Noise spectra of suction unit working at different operating conditions are presented in Fig. 7. Suction unit generates lower total noise level at partial flow rates and at higher-pressure rise than at maximum flow rate and lower pressure raise. Suction unit generates lowest total noise levels when it works at the designed operating condition.
By observing different noise spectra, a characteristic frequency range and discrete frequencies which contribute significantly to overall noise level, were identified (28*RF and 42*RF and BBN, in Figs. 4, 5 and 7). To determine their exact spatial origin noise source visualization was applied (Figs 8-12).

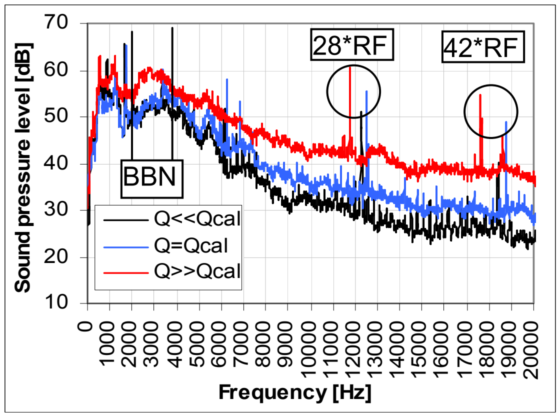

Fig. 7. Noise spectra of suction unit working under three different operating conditions and constant voltage supply

The non-rotational aerodynamic noise is a result of laminar and turbulent boundary layer vortex shedding at higher flow rates ($Q > Q_{des}$), and blade interaction with the blade tip clearance vortices and blade stall and surge phenomena at partial flow rates ($Q < Q_{des}$). Among non-rotational noise generating mechanisms, the surge phenomenon is the most important one, and has a strong effect on the structure-borne noise of the suction unit as whole. Total emitted noise is a sum of the rotational and non-rotational noise. Since the rotational noise theoretically does not depend on the load, and the non-rotational noise increases at off-design operation, the total noise level usually has its minimum at the BEP. At design as well as at off-design operation the aerodynamically generated broadband noise within the blower mostly prevails in the total emitted noise, (Figs. 8 and 12).

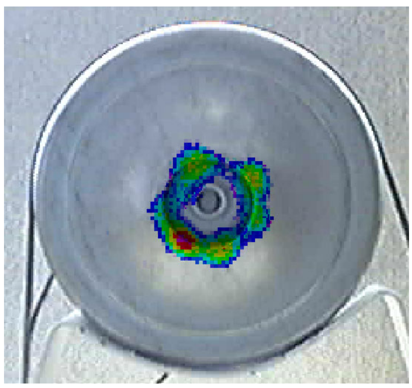

Fig. 8. Total sound pressure pattern at free delivery. Aerodynamic rotational and non-rotational noise from blower dominates

At higher flow rates ($Q > Q_{des}$) the non-rotational noise constantly increases due to the air jet flows from the electric motor openings and laminar and turbulent boundary layer vortex shedding caused by flow declination and turbulence, Figs. 8 and 12.
Turbulent noise of aerodynamic origin increases steadily with flow rate and gradually overlaps the structure-borne non-rotational noise (pronounced at the lower frequencies) as well as rotational noise at the rotational frequency, at the blade passage frequency, and their higher harmonics. At higher rotational speed and free delivery, the aerodynamic noise fully dominates within the almost entire frequency range observed.

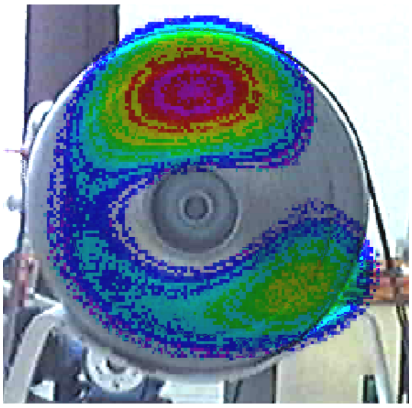

Fig. 9. Acoustic photo of discrete frequency, which corresponds to eigenfrequency of the housing plate

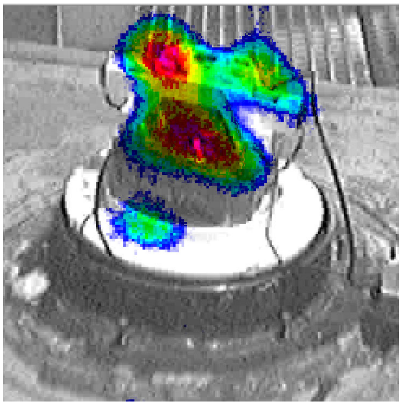

Fig. 10. Acoustic picture of broadband noise in frequency range from 2250 to 3000 Hz, depicted with BBN in Fig.4

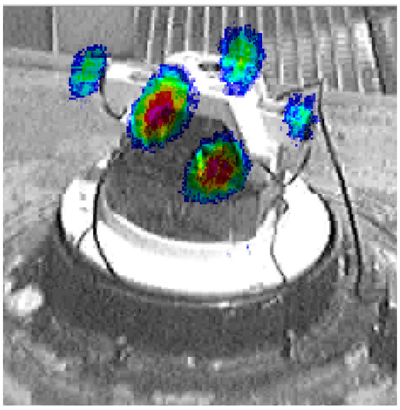

Fig. 11. Acoustic picture of discrete frequency 42*RF. Brush noise and bearing noise.

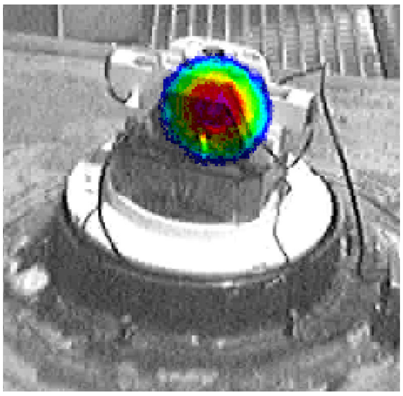

Fig. 12. Acoustic picture of rotation frequency and its first harmonic 2*RF

At partial flow rates ($Q < Q_{des}$), the non-rotational noise constantly increases due to the rotating stalls and surge phenomena, the turbulence caused by the flow declination on the leading edges of the rotor blades, and due to vortices in air clearances between the rotor and stator, and gradually overlaps the rotational one, Figs. 10 to 12.

7. Conclusions

The emitted noise of a suction unit is generated partially by the turbo blower and partially by the driving electric motor. The blower is the main source of aerodynamically generated noise, whereas the electric motor is the origin of mechanical and electromagnetic noise.
From the analyses, we can conclude that the rotational noise usually prevails at the design point of operation, and that the non-rotational noise prevails at off-design operation. The main source of noise within a suction unit can be attributed to the origins of the aerodynamically generated noise, at the design as well as at off-design operation. Measurement results have shown that the total noise level has its minimum at the BEP and that at off-design operation its level increases.
At higher flow rates ($Q > Q_{des}$), it gradually increases due to the laminar and turbulent boundary layer vortex shedding, and due to the air flow from the electric motor openings.
At partial flow rates ($Q < Q_{des}$), the emitted noise increases mainly due to the rotating stalls and surge phenomena, and due to the vortices in air clearances between the rotor and stator.
The main source of the noise is therefore the blower. The main noise is coming from the part belonging to the electric motor openings at the brushes.

8. References

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