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Hrup aksialnih ventilatorjev pri delnih pretokih

Noise of Axial Cooling Fans at Partial Flow Rates

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Pri zračno hlajenih dieselskih motorjih je aksialni ventilator pomemben vir hrupa. Osnovna značilnost aksialnih ventilatorjev je, da imajo v območju delnih pretokov zaradi nestabilnega delovanja neugoden potek karakteristik. Nestabilen režim obratovanja je posledica nastajanja rotirajočih zastojnih vrtincev, ki se praviloma pojavijo v rotorju in/ali vodilniku ventilatorja. Zastojni vrtinci povzročajo poleg naglega povečanja hrupa še poslabšanje delovanja in pojav črpanja. Točke črpanja definirajo t.im. mejo črpanja, ki pomeni spodnjo mejo obratovanja ventilatorja. Meja črpanja je odvisna od narave in intenzivnosti zastojnih vrtincev, ti pa spet od geometrijske oblike ventilatorja in obratovalnih razmer. V literaturi obstajajo različne razlage za nastanek zastojnih vrtincev in njihov učinek na oddano raven hrupa in njegov spekter. V tem prispevku so osvetljeni ti pojavi na podlagi teorije kaskad in spektralne analize hrupa ventilatorja. Podana je tudi korelacija med diskretno frekvenco t.im. nerotirajočega hrupa zaradi nastajanja zastojnih vrtincev in frekvenco vrtenja rotorja ventilatorja.

An axial cooling fan in an air-cooled diesel engine is one of the important noise sources. The main characteristics of axial flow fans are instabilities in their performance and noise characteristics at partial flow rate. The instabilities in fan operation are a consequence of rotating stalls created in the rotor blade and/or in guide vane cascade. The rotating stalls cause a steep increase in the emitted noise and lower the performances of the fan. At some operation conditions the rotating stalls also cause an appearance of surge. The surge points determine the surge line which represents the lowest region of fan operation. At given operation conditions and fan's geometry, the surge line depends on the nature and intensity of the rotating stalls. In the available literature there are different explanations of the rotating stall generation and its influence on the emitted noise level and its spectra. The present paper highlights these phenomena using the theory of cascades and noise spectra analysis. Correlation between the discrete frequency of the non-rotational noise caused by the rotational stall and rotational frequency of the fan is also provided.

0 UVOD

Pri zračno hlajenih dieselskih motorjih uporabljamo za pretok hladilnega zraka aksialni ventilator. Aerodinamični hrup aksialnega ventilatorja je širokopasoven z izrazitimi toni določenih frekvenc ali brez njih. Širokopasoven spekter hrupa z izrazitimi toni teh frekvenc imenujemo rotirajoči hrup, tistega, pri katerem prevladuje širokopasovni hrup, pa nerotirajoči hrup [1], [2].

Rotirajoči hrup je predvsem posledica fluktuirajočih sil na lopaticah rotorja in interakciji gonilnih lopatic z vstopnimi in/ali izstopnimi motnjami, to so: vodilne lopatice, oporna ali nosilna rebra, zaščitna mreža ali pogonski jermen. Hrup, ki se tako ustvarja, je tonalnega značaja in je v zvezi s frekvenco vrtenja rotorskih lopatic (FVRL). Ta frekvenca ni mnogokratnik števila lopatic, če delitev lopatic ni enaka, ampak se razprši na več vrhov manjših amplitud okrog neke osrednje FVRL.

0 INTRODUCTION

In air-cooled diesel engines, axial fans are used to provide the flow of cooling air. The aerodynamic noise of an axial fan can be a broadband noise with superimposed tones of discrete frequencies or without them. A broadband noise spectrum with superimposed discrete frequency tones is named rotational noise, while the noise in which the broadband spectrum is predominant is termed non-rotational [1], [2].

The rotational noise is mainly caused by fluctuating forces on the rotor blades and blade interaction with inlet and outlet distortions such as: guide vanes, struts, protective grid and fan driving belt. The noise generated in this way is tonal by nature and is related to the rotor blade rotation frequency or blade passage frequency (BPF). This frequency is not a multiplier of the number of blades, if the blade spacings are not uniform, but disperses into several minor amplitude peaks around one central BPF.

Rotirajoči hrup karakterizira veliko število harmonikov, med katerimi so zlasti izraziti prvi trije. Ker je praktično neodvisen od obremenitve, rotirajoči hrup prevladuje pri srednjih in večjih pretokih.

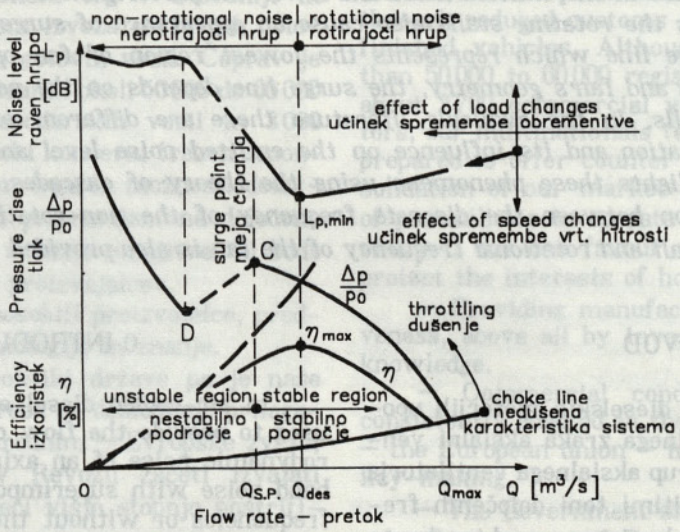
Nerotirajoči hrup je posledica različnih mehanizmov nastajanja hrupa, npr.: a) razkrajanje vrtinca v laminarni mejni plasti na sesalni strani lopatic rotorja, b) interakcija vrha rotorskih lopatic z vrtincem, nastalim v špranji med cevjo in vrhom lopatic rotorja ter c) nastanek rotirajočih zastojnih vrtincev v kaskadi rotorskih in/ali vodilnih lopatic. Ta vrsta hrupa prevladuje pri manjših pretokih oz. pri delnih obremenitvah in ni povezan s frekvenco vrtenja rotorja (FVR) ali rotorskih lopatic (FVRL).

Ker rotirajoči hrup prevladuje pri večjih in nerotirajoči hrup pri manjših pretokih, se pojavi minimalna raven hrupa pri pretoku med tema dvema režimoma (sl. 1). Absolutna vrednost celotne ravni hrupa je odvisna od relativnih vrednosti ravni obeh virov (rotirajočega in nerotirajočega) hrupa ter, pri dani geometrijski obliki ventilatorja, od obratovalnih razmer oziroma od pretoka in vrtilne hitrosti ventilatorja. Najmanjša raven hrupa se praviloma pojavi v računski točki oz. pri največjem izkoristku η_{max}, [1], [2], [3].

The rotational noise is characterized by a large number of harmonics among which the first three are especially predominant. As the rotational noise is practically independent of the load, it is the predominant type of noise in medium and high flow rates.

The non-rotational noise is a result of several noise generating mechanisms such as: a) laminar boundary layer vortex shedding on the blade suction side, b) blade interaction with the tip clearance vortex, and c) blade stalls in the rotor and/or guide vane cascades. This type of noise predominates at low flow rates or partial loads and is not related to the rotor rotating frequency (RRF) or BPF.

Since the rotational noise predominates at higher and non-rotational at lower flow rates, the minimum level of noise occurs at the flow rate between these two regimes (Fig. 1). The absolute value of the total noise level depends on the relative values of both (rotational and non-rotational) noise sources, and, at a given fan geometry, on the flow rate and rotating speed of the fan. The minimum noise level normally occurs in the design point or at maximum efficiency η_{max} [1], [2], [3].



Sl. 1. *Karakteristike ventilatorja*

Fig. 1. *Fan characteristics*

Med vsemi mehanizmi nastajanja nerotirajočega spektra hrupa je tisti zaradi nastanka rotirajočih zastojnih vrtincev v lopatičnih kaskadah najmočnejši, saj povzroči zelo naglo povečanje hrupa – tudi do 15 dB(A) in več. Značilnost tega mehanizma nastajanja hrupa je, da ima vrh pri nizkih frekvencah, ki niso večkratniki FVR ali FVRL in njunih harmonikov. Poleg tega rotirajoči zastojni vrtinci povzročajo t.im. pojav črpanja in nestabilnost v obratovanju ventilatorja, tako da prihaja do

Among all mechanisms generating non-rotational noise, the one due to rotating stalls in the blade cascades is the most intensive, causing a steep increase in noise level even up to 15 dB(A) and more. A characteristic of this type of noise generating mechanism is that it reaches its peak at low frequencies which are not multipliers of RRF and BPF and their harmonics. Besides that, the rotating stalls can cause the occurrence of so-called surge which results

močnega zmanjšanja tlaka in pretoka in s tem do nezadostnega hlajenja motorja in njegovega pregrevanja. Poleg tega se močno zmanjša tudi izkoristek ventilatorja. Zaradi vseh naštetih posledic, ki se pojavijo z rotirajočimi zastojnimi vrtinci, nas zanimajo mehanizmi, ki sprožijo vrtince, in v kakšnih razmerah in pri katerih frekvencah ti nastajajo.

1 NASTAJANJE ROTIRAJOČIH ZASTOJNIH VRTINCEV

S preizkusi je bilo ugotovljeno, da nastaneta dva neodvisna zastojna vrtinca, ob pestu (A) in ob vrhu lopatice (B) (sl. 2a) [4]. Rotirajoči zastojni vrtinci nastanejo, pri dani geometrijski obliki rotorskih lopatic, zaradi dušenja oz. spremembe obremenitve ventilatorja. Mehanizem nastajanja hrupa najlaže razložimo z uporabo glavne turbinske enačbe za neskončno število lopatic in tok brez trenja:

in instability of operation, a substantial drop in pressure and airflow rate, and thus insufficient cooling of the engine and its consequent overheating. In addition, we can also note a drastic drop in the fan's efficiency. In order to avoid all these negative effects caused by blade stalls, the purpose of our research was to study the stall generating mechanisms, and the conditions and frequencies at which stalls usually occur.

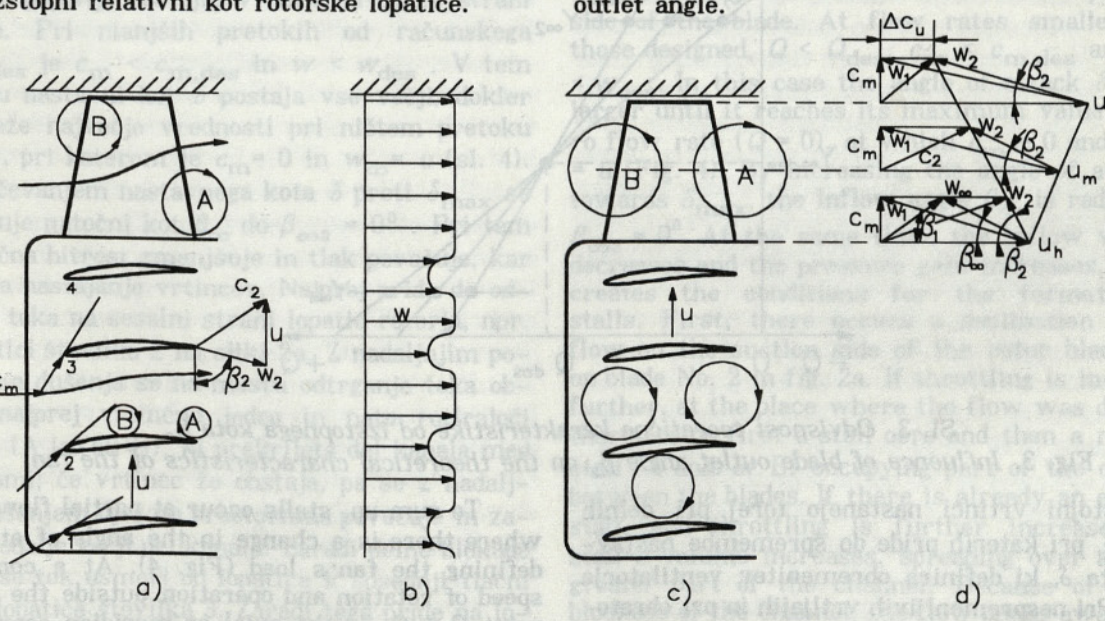
1 BLADE STALL GENERATION

Experiments have shown that two independent stalls are generated, one at the hub (A) and one at the blade tip (B) (Fig. 2a), [4]. At the given rotor blade geometry, rotating stalls occur as a result of fan throttling or change in fan loads. The mechanism of generating the noise is easiest to be explained by means of the main turbine equation for an infinite number of blades and inviscid flow:

$$Y_\infty = u c_{u2} = u \Delta c_u = u^2 - u c_m \cot\beta_2 = u^2 - u \frac{Q}{S} \cot\beta_2 \qquad (1),$$

pri čemer so: Y_∞ — specifična energija, ki je enaka za vse valjaste prereze od pesta do zunanjega premera rotorja, $u = D\pi n$ — obodna hitrost, c_u in c_m — sta obodna in meridianska komponenta absolutne hitrosti, Q — pretok, S — pretočni prerez in β_2 — izstopni relativni kot rotorske lopatice.

where: Y_∞ is specific energy, which is constant for all cylindrical cross-sections, $u = D\pi n$ peripheral speed, c_u and c_m peripheral and meridian components of absolute speed, Q flow rate, S flowrate cross-section and β_2 relative blade outlet angle.



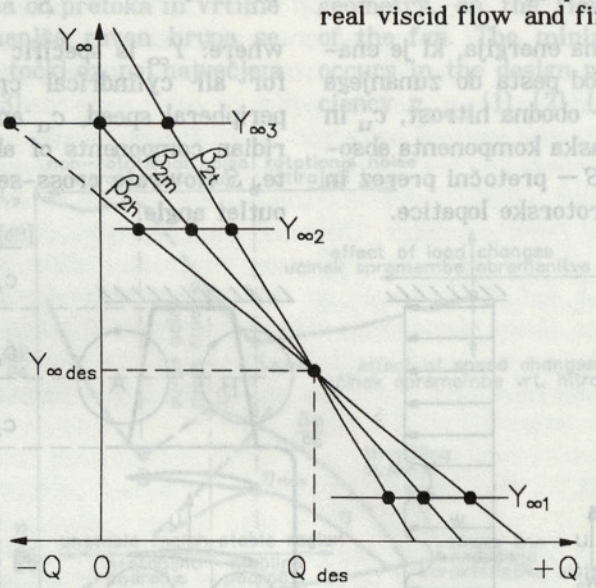
Sl. 2. *Nastajanje zastojnih vrtincev v lopatični kaskadi in trikotniki hitrosti*
Fig. 2. *Blade stall generation and its evolution with triangle velocity*

Ker je c_m pri aksialnih ventilatorjih na vseh valjastih prerezih po višini lopatice konstantna, je za dosego pogoja Y_∞= konst potrebno, da se s povečevanjem radija in obodne hitrosti u od pesta do zunanjega oboda rotorja zmanjšuje vrednost c_{u2} oz. Δc_u (sl. 2d). Zaradi tega se z zmanjševanjem

Since in axial fans, on all cylindrical cross-sections along the blade height c_m is constant, in order to fulfill the condition Y_∞ = constant it is necessary that, by increasing the radius and the peripheral speed u from the hub to the tip diameter, the values c_{u2} or Δc_u are decreased (Fig. 2d). As a result of this, by decreasing the value

vrednosti Δc_u, zmanjšuje kot β_2 od pesta proti obodu rotorja. Grafični prikaz enačbe (1) na karakterističnih prerezih rotorja (h — ob pestu, m — na sredini in t — na vrhu lopatice) je prikazan na sliki 3. S te slike vidimo, da je pri vrednosti $Y_{\infty 1}$, pri $Q > Q_{des}$ pretok ob pestu večji kakor ob vrhu lopatice. Pri $Q < Q_{des}$ je pri $Y_{\infty 2}$ prav nasprotno. Pri $Y_{\infty 3}$ postane pretok ob pestu celo nasproten, kar pomeni, da teče tok zraka nazaj proti lopatici. Povratni negativni tok se pojavi samo ob sesalni — hrbtni površini lopatice rotorja, medtem ko tok zapušča rotorske kanale ob tlačni strani sosednje lopatice, in sicer na nekem večjem radiju, kakor je vstopil v kaskado, (sl. 2a). Zato nastanejo rotirajoči zastojni vrtinci, ki se pojavijo pri manjših kotih lopatic. To pomeni pri izstopu iz rotorja ob pestu (vrtinec A) in pri vstopu v rotor ob vrhu lopatice (vrtinec B na sl. 2a). Vrtinca (A) in (B) zmanjšata pretočni prerez skozi lopatično kaskado in usmerjata tok navzven proti obodu rotorja v obliki vijačnice (sl. 2a). Ta teoretična razlaga velja tudi pri realnem toku s trenjem in pri končnem številu lopatic [4].

Δc_u, the angle β_2 decreases from the hub to the tip diameter. A graphical presentation of equation (1) for the characteristic rotor cross-sections (h — at the hub, m — in the middle and t — at the blade tip) is shown in figure 3. From fig. 3 we can see that at a value $Y_{\infty 1}$, at $Q > Q_{des}$, the flow rate at the hub is greater than at the blade tip. On the other hand, at $Q < Q_{des}$ and $Y_{\infty 2}$ it is quite the opposite. At $Y_{\infty 3}$ the flow rate at the hub becomes even negative, which means that the air flows back towards the blade. The reverse or negative flow occurs only along the suction or back side of the rotor blade, whereas the flow leaves the rotor channels along the pressure side of the adjacent blade, and at a larger radius than that of its entry into the cascade (Fig. 2a). A result of this is the formation of rotating stalls occurring at smaller blade angles, which means on the exit from the rotor at the hub (stall A) and at the entry into the rotor at the blade tip (stall B, Fig. 2a). The blade stalls (A) and (B) reduce the flow rate cross-section through the blade cascade and direct the flow outwards to the rotor periphery, thus forming a screw flow (Fig. 2a). This theoretical explanation is valid also for a real viscid flow and finite number of blades, [4].

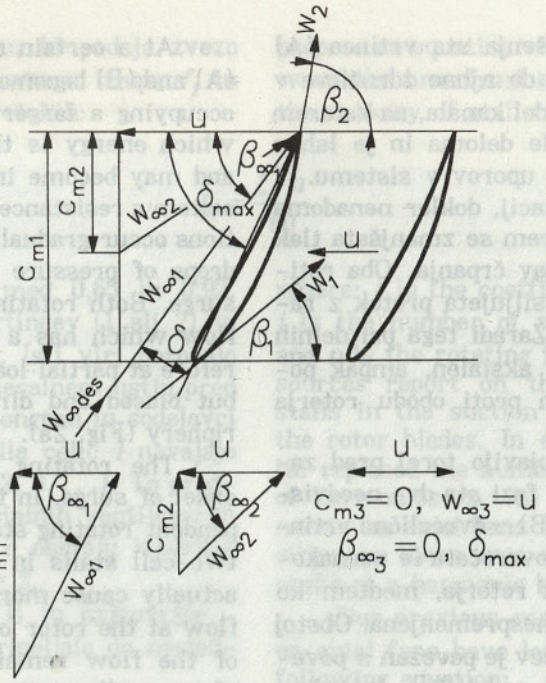


Sl. 3. *Odvisnost teoretične karakteristike od izstopnega kota β_2*

Fig. 3. *Influence of blade outlet angle β_2 on the theoretical characteristics of the fan*

Zastojni vrtinci nastanejo torej pri delnih pretokih, pri katerih pride do spremembe nastavnega kota δ, ki definira obremenitev ventilatorja (sl. 4). Pri nespremenljivih vrtljajih in pri obratovanju ventilatorja zunaj računske točke $Q \neq Q_{des}$ se aksialna oz. meridianska komponenta absolutne hitrosti c_m spremeni ustrezno s kontinuitetnim zakonom $Q = A\,c_m$. S spremembo aksialne hitrosti se spremeni tudi relativna hitrost toka w v rotorskih kanalih po enačbi $w_\infty = c_m/\sin\beta_\infty$ (sl. 4). Zaradi spremembe relativne hitrosti se spremeni natočni kot β_∞ in nastavni kot δ. Spremeni se torej obremenitev lopatic.

To sum up, stalls occur at partial flow rates where there is a change in the angle of attack δ defining the fan's load (Fig. 4). At a constant speed of rotation and operation outside the design point $Q \neq Q_{des}$, the axial or meridian component of the absolute velocity c_m changes in conformance with the continuity law $Q = A\,c_m$. With the change of the axial velocity c_m, the relative flow velocity w in the rotor channels also changes according to equation $w_\infty = c_m/\sin\beta_\infty$, (Fig. 4). A result of the change in relative velocity is the change in the relative blade angle β_∞ and angle of attack δ. Thus, all these factors produce a change in the blade load.



Sl. 4. *Vpliv obremenitve na nastavni kot lopatic* δ

Fig. 4. *Influence of fan load on the angle of attack* δ

Pri večjih pretokih od računskega $Q > Q_{des}$ je $c_m > c_{m,des}$ in $w > w_{des}$. Pri tem nastavni kot δ postaja vse manjši, dokler ne doseže ničte vrednosti pri prostem pretoku (pri Q_{max}). V tem primeru se pojavijo zastojni vrtinci na tlačni strani lopatice. Pri manjših pretokih od računskega $Q < Q_{des}$ je $c_m < c_{m,des}$ in $w < w_{des}$. V tem primeru nastavni kot δ postaja vse večji, dokler ne doseže največje vrednosti pri ničtem pretoku ($Q = 0$), pri katerem je $c_m = 0$ in $w_\infty = u$ (sl. 4). S povečevanjem nastavnega kota δ proti δ_{max} se zmanjšuje natočni kot β_∞ do $\beta_{\infty 3} = 0^0$. Pri tem se natočna hitrost zmanjšuje in tlak povečuje, kar omogoča nastajanje vrtincev. Najprej pride do odtrganja toka na sesalni strani lopatic rotorja, npr. na lopatici številka 2 na sliki 2a. Z nadaljnjim povečanjem dušenja se na mestu odtrganja toka oblikuje najprej vrtinčno jedro in nato rotirajoči vrtinec (A in/ali B), ki prekrijeta del kanala med lopaticami; če vrtinec že obstaja, pa se z nadaljnjim dušenjem njegova prostornina povečuje in zakriva čedalje večji del kanala. Zaradi delne blokade kanala se tok usmeri od lopatice k sosednji tlačni strani lopatice številka 3. Zaradi tega pride na lopatici številka 3 do povečanja nastavnega kota, medtem ko pride ob lopatici številka 1 do zmanjšanja nastavnega kota δ. Zaradi tega se bo rotirajoči zastojni vrtinec širil v smeri od lopatice 1 proti 2, 3, 4 itn. Rotirajoči zastojni vrtinci potujejo torej v smeri rotacije in rotirajo s hitrostjo, ki je manjša od vrtilne hitrosti rotorja. Hitrosti vrtincev se lahko spreminjajo od 10 do 90 odstotkov hitrosti rotacije gredi [9].

At higher flow rates than the design rate, $Q > Q_{des}$, $c_m > c_{m,des}$ and $w > w_{des}$. Here the angle of attack δ becomes increasingly smaller until it reaches its zero value at choke line (at Q_{max}). In this case stalls occur on the pressure side of the blade. At flow rates smaller than those designed, $Q < Q_{des}$, $c_m < c_{m,des}$ and $w < w_{des}$. In this case the angle of attack δ grows larger until it reaches its maximum value at zero flow rate ($Q = 0$), at which $c_m = 0$ and $w_\infty = u$ (Fig. 4). By increasing the angle of attack δ towards δ_{max}, the inflow angle β_∞ is reduced to $\beta_{\infty 3} = 0^0$. At the same time, the inflow velocity decreases and the pressure gain increases, which creates the conditions for the formation of stalls. First, there occurs a declination of the flow on the suction side of the rotor blade, e.g. on blade No. 2 in fig. 2a. If throttling is increased further, at the place where the flow was declined there forms first a stall core and then a rotating stall (A and/or B) occupying part of the channel between the blades. If there is already an existing stall, and throttling is further increased, the stall's volume increases, spreading over an ever greater part of the channel. Because of partial blockade of the channel, the flow bends away from the blade and directs itself towards the adjacent pressure side of blade No. 3. As a result, on blade No. 3 the angle of attack increases, while along blade No. 1 it decreases. The rotating stall spreads in the direction from blade 1 towards 2, 3, 4 etc. Thus the rotating stalls spread in the direction of rotation and rotate at a speed lower than the rotating speed of the rotor. The velocity of the stalls may vary from 10 to 90 % of the rotor speed, [9].

Pri določeni stopnji dušenja sta vrtinca (A) in (B) tako velika, da pride do njune združitve v en vrtinec, ki prekrije večji del kanala, na katerem se potem energija prenaša le deloma in je lahko nezadostna za premagovanje uporov v sistemu. V tej fazi pride do tlačnih pulzacij, dokler nenadoma ne pride do kolapsa, pri katerem se zmanjšata tlak in pretok, nastane t.im. pojav črpanja. Oba rotirajoča vrtinca (A) in (B) vsiljujeta pretok z radialno komponento hitrosti. Zaradi tega pri delnih obremenitvah pretok ni več aksialen, ampak poševen in usmerjen navzven proti obodu rotorja (sl. 2a).

Rotirajoči vrtinci se pojavijo torej pred začetkom pojava črpanja. V tej fazi sta dva neodvisna rotirajoča vrtinca (A) in (B) — dvocelična vrtinca na sliki 2a, ki dejansko povzročata le neenakomernost toka pri izstopu iz rotorja, medtem ko povprečna masa toka ostane nespremenjena. Obstoj dvoceličnih rotirajočih vrtincev je povezan s povečanim nastajanjem hrupa. Z nadaljnjim dušenjem prihaja do ekspanzije vrtincev, njihovega dotika in celo združitve. Pri tem se zapolni večji del pretočnega prereza lopatične kaskade najprej z dvema in na koncu samo še z enim velikim vrtincem (sl. 2c). Pride do omenjenega pojava črpanja z močnimi pulzacijami tlaka in zelo intenzivnim nastajanjem akustičnega tlaka oz. hrupa, ki je večji, tudi do 15 dB(A). Nastali hrup slišimo kot globinsko šumenje in bobnenje, podobno tistemu ob močnem potresu. V fazi črpanja, ko se vrtinca združujeta, prihaja do globalne oscilacije masnega toka v celotnem ventilatorju. Z nadaljnjim dušenjem proti pretoku $Q \approx 0$, se raven celotnega spektra hrupa enakomerno še naprej povečuje z vrhom spektra pri približno isti frekvenci. Pri $Q = 0$, ko ni več cirkulacije, obstaja en sam vrtinec, ki zapolni celotni prerez kanala med lopaticami.

Pri pojavu črpanja se prenos energije trenutno premakne na nižjo raven tlaka pri manjšem pretoku, obratovalna točka takoj preskoči iz točke C v točko D na sliki 1. Meja črpanja se pri dani geometrijski obliki ventilatorja ne spreminja; običajno se pojavi pri 70 do 80 odstotkih računskega pretoka. Na karakteristiki poteka tlaka v odvisnosti od pretoka (sl. 1) je meja črpanja tista, ki loči stabilni od nestabilnega področja obratovanja ventilatorja. Meja črpanja se pojavi tem prej, čim večja sta kot lopatice β_1 in nastavni kot δ ter čim manjši je izstopni kot rotorske lopatice β_2 .

Nerotirajoči ali širokopasovni spekter hrupa ima vrh pri dveh značilnih frekvencah, ena je pod, druga pa nad prvim harmonikom FVRL. Glede vzrokov za pojav vrha pri teh dveh frekvencah ni enotnega mnenja. Nekateri avtorji [7], [8], ki so raziskovali ta pojav na centrifugalnih

At a certain degree of fan throttling, stalls (A) and (B) become so big that they merge into one occupying a larger part of the blade channel, in which energy is then only partially transmitted and may become insufficient for overcoming the sistem's resistance. In this phase, pressure pulsations occur gradually leading to a collapse, drastic drops of pressure and, to a phenomenon termed surge. Both rotating stalls (A) and (B) impose a flow which has a radial speed component. Therefore at partial loads the flow is no longer axial, but biased and directed towards the rotor periphery (Fig. 2a).

The rotating stalls thus occur before the onset of surge. In this phase there are two independent rotating stalls (A) and (B) which are the two-cell stalls in figure 2a, and which do not actually cause more than non-uniformity of the flow at the rotor outlet, while the average mass of the flow remains unchanged. The existence of two-cell rotating stalls is related to increased noise generation. With further throttling, the stalls expand, touch each other and even merge into one, i.e. a one-cell stall. Thus a major part of the channel of the blade cascade is occupied first by two, and later by only one large stall (Fig. 2c). The occurrence of surge is accompanied by strong pressure pulsations and very intensive generation of acoustic pressure or noise that may reach even 15 dB(A). The generated noise is heard as a deep-down rush or booming similar to that in a powerful earthquake. In the phase of surge, when the stalls merge, the mass flow oscillates globally in the entire fan. With further throttling towards $Q \approx 0$, the level of the total noise spectrum increases uniformly, with the spectrum peak at approximately the same frequency. At $Q = 0$, when there is no circulation any more, there exists only one stall filling the entire cross-section of the channel between blades.

In the occurrence of surge the energy transfer temporarily moves to a lower pressure level and flow rate, from point C to point D in figure 1. For a given fan geometry, the surge point does not change; it usually occurs at 70 to 80 % of the design flow rate. In the flow-pressure characteristic (Fig. 1), the surge point is the one that separates the unstable operating region from the stable one. The surge point occurs the sooner, the larger is the blade angle β_1 and the angle of attack δ, and the smaller is the blade outlet angle β_2 .

The non-rotational noise or broadband noise spectrum has its peak at two characteristic frequencies, one is below and the other above the first harmonic of the BPF. There is no single explanation for the reasons why the peak occurs at these two frequencies. Some authors [7], [8] who studied this phenomenon on centrifugal fans,

ventilatorjih, predlagajo enačbo, ki podaja zvezo med frekvenco vrha širokopasovnega hrupa f_i in hitrostjo vrtincev pri delnih pretokih:

$$f_i = \frac{\xi i n}{60} \quad (2),$$

pri tem so: ξ — koeficient med 0,65 in 0,92, i — število celic rotirajočih vrtincev (1 ali 2) in n — vrtilna frekvenca (min^{-1}). Isti viri poročajo o pojavu zastojnih vrtincev v sesalnem ustju pred vstopom v rotorske lopatice. Mongeau in sodelavci [9] v enačbi (2) namesto števila celic i navajajo število harmonskih m, (m = 1, 2, 3, . . .). To predpostavko naši preizkusi na aksialnih ventilatorjih niso potrdili, saj ni znamenja o obstoju izrazitih vrhov pri višji harmski od m = 2.

Naše prejšnje raziskave [1] in najnovejše na aksialnih ventilatorjih so pripeljale do naslednje oblike enačbe:

$$f_i = \frac{\xi z i n}{60} \quad (3).$$

Enačba (3) se razlikuje od enačbe (2) za število lopatic rotorja z, kar izhaja iz teorije o nastanku rotirajočih vrtincev pri aksialnih ventilatorjih v vseh kanalih rotorskih lopatic. Ta teorija temelji tudi na predpostavki o oblikovanju najprej dveh vrtincev, ki se v bližini meje črpanja združita v enega (sl. 2a in 2c). Koeficient ξ podaja dejansko faktor zaostajanja rotacije obeh vrtincev (dokler sta ločena in po združitvi) za hitrostjo rotacije lopatic rotorja. Ta hitrost rotacije vrtincev ni konstantna, ampak se nekoliko spreminja zaradi njune nestacionarne narave in zaradi resonance sistema [10].

Odlepljanje toka od površine lopatic pri delnih pretokih, pri $Q < Q_{des}$, se pojavlja tudi na lopaticah vodilnika. Na vodilniku, nameščenim za rotorjem, celo prej kakor v rotorju. V vodilnih lopaticah se pojavi rotirajoči vrtinec zaradi močne interakcije med mejnimi plastmi na stenah lopatične kaskade vodilnika in neviskoznih jeder toka. Ker je tok pri izstopu iz rotorja usmerjen proti obodu oz. proti vrhu lopatic (sl. 2a), se vrtinci v lopatični kaskadi vodilnika pojavijo ob pestu.

2 PRIKAZ EKSPERIMENTALNIH REZULTATOV IN OBRAVNAVA

Pojav nerotirajočega spektra hrupa smo eksperimentalno opazovali na TAM-ovih ventilatorjih Ø 400 mm (NLG 312/400-11/17 z vodilnikom, postavljenim za rotorjem) in Ø 360 mm (VLG

propose an equation which defines the relation between the broadband noise peak frequency f_i and the velocity of stalls at partial flow rates:

where: ξ is the coefficient between 0.65 and 0.92, i is the number of rotating stall cells (1 or 2) and n is the rotating frequency (RPM). The same sources report on the phenomenon of rotating stalls in the suction mouth before the inlet of the rotor blades. In equation (2) Mongeau et al. [9] replaced the number of cells i by the number of harmonics m, (m =1, 2, 3, ...). Our experiments on axial fans did not confirm this supposition as there was no sign of the existence of peaks at a harmonic higher than m = 2.

Our previous research [1] and newest tests on axial fans have led to the formulation of the following equation:

Equation (3) differs from equation (2) by the number of rotor blades z, which follows from the theory about the formation of rotating stalls in axial fans in all rotor blade channels. This theory is based also on the supposition that in the beginning just two stalls are formed which then merge into one before the surge point (Fig. 2a and 2c). The coefficient ξ defines the actual factor of retardation of the rotation of both stalls (until separated and also after their merger) behind the rotor blade rotating speed. The speed of blade stall is not constant but changes slightly because of their non-stationary nature and the resonance of the system, [10].

At partial flow rate, at $Q < Q_{des}$, the stall can also occur on guide vanes. In cases when the guide vane is placed behind the rotor, it occurs on guide vanes even earlier than in the rotor. In the guide vanes the rotating stall occurs as a result of strong interaction between the boundary layers on the guide vane cascade walls and inviscid core flow. Since, on exit from the rotor, the flow is directed towards the blade tips (Fig. 2a), the stalls in the guide vane cascade occur at the hub.

2 EXPERIMENTAL RESULTS AND DISCUSSION

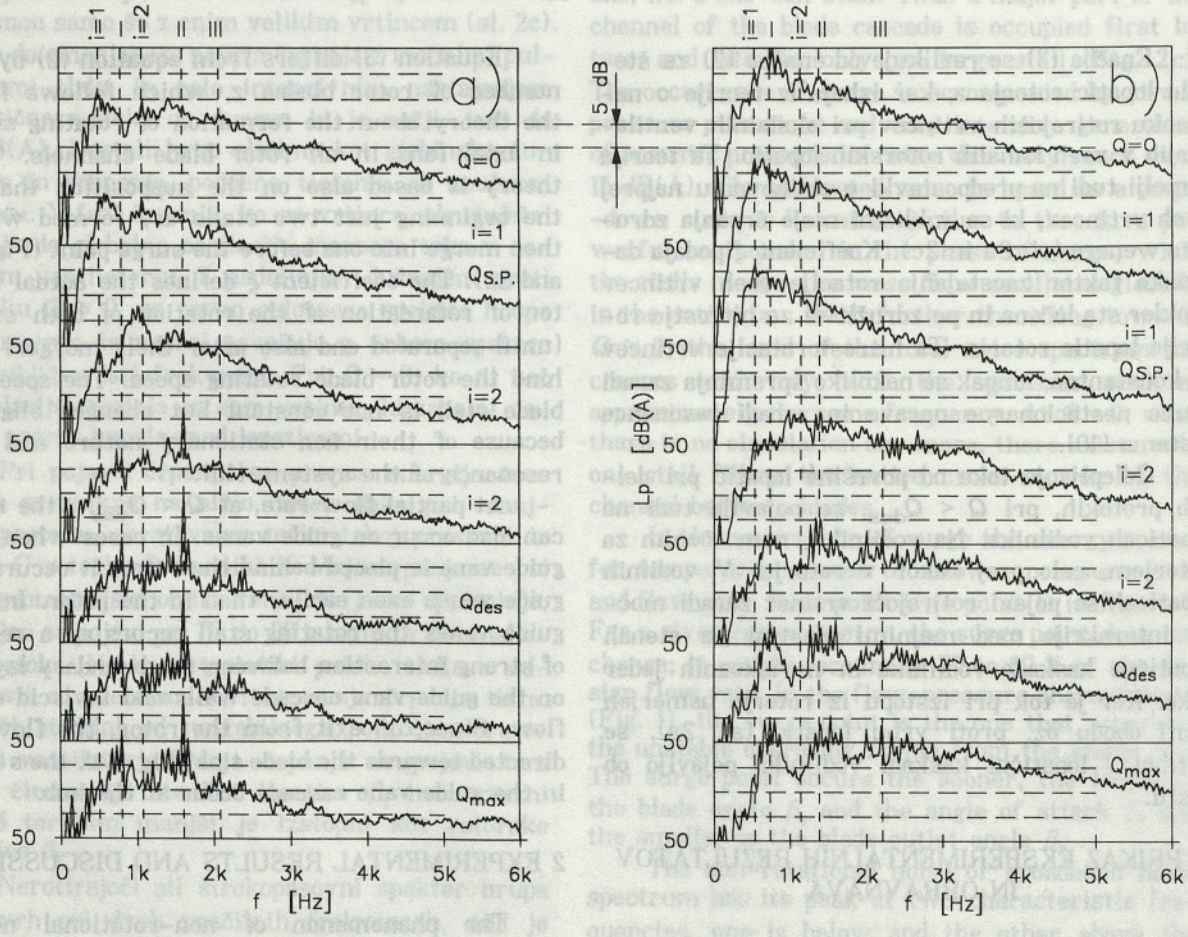
The phenomenon of non-rotational noise spectrum was experimentally tested on TAM fans with Ø 400 mm (NLG 312/400-11/17 with the guide vanes placed behind the rotor) and with Ø 360 mm (VLG 215/360-18/11 with the

215/360-18/11 z vodilnikom, postavljenim pred rotorjem). Pri obeh ventilatorjih je število lopatic $z = 11$ in kot rotorske lopatice na zunanjem premeru $\gamma = 21^0$. Raven in spekter hrupa sta merjena pri različnih stopnjah dušenja ventilatorja (od Q_{max} do $Q = 0$) in pri štirih različnih vrtilnih frekvencah (3500, 4000, 4500 in 5000 min^{-1}) na razdalji 1 m od osi ventilatorja, pod kotom 45^0 in v razmerah prostega zvočnega polja (v gluhi komori).

Na sliki 5 je prikazana serija spektrov hrupa, posnetih pri 4000 min^{-1} na ventilatorju Ø 400 mm (sl. 5a) in Ø 360 mm (sl. 5b). Iz spodnjega spektra, ki ustreza največjemu pretoku Q_{max}, vidimo, da prevladuje spekter rotirajočega hrupa z izrazitimi toni diskretnih frekvenc, ki ustrezajo prvi (I), drugi (II) in tretji (III) harmonski FVRL. Teoretično bi morali biti vrhovi teh treh harmonskih pri 733, 1466 in 2200 Hz. Praktično se pri vsaki harmonski pojavi več vrhov, zaradi neenakomernih delitev lopatic (5 različnih delitev). Kakor vidimo iz spektrov hrupa na slikah 5a in 5b, se največji vrhovi pojavijo pri različnih

guide vanes placed before the rotor). In both fans the number of blades was $z = 11$, and the blade pitch angle was $\gamma = 21^0$. The level and spectrum of the noise were measured at different throttling rates (from Q_{max} to $Q = 0$) and four different rotating speeds (3500, 4000, 4500 and 5000 RPM) at a distance of 1 m from the fan axis, at an angle of 45^0 and in the conditions of a free field environment (anechoic chamber).

Figure 5 shows a series of noise spectra recorded at 4000 RPM on the fan with Ø 400 mm (Fig. 5a) and on the fan with Ø 360 mm (Fig. 5b). From the bottom spectrum corresponding to the maximum flow rate Q_{max} we can see that the predominant form is the rotating noise spectrum with distinct discrete frequency tones corresponding to the first (I), second (II) and third (III) harmonic of the BPF. Theoretically the peaks of these three harmonics should be at 733, 1466 and 2200 Hz. In practice, however, at each harmonic several peaks are formed as a result of non-uniformly spaced blades (five different divisions). As seen from figures 5a and 5b, the highest peaks occur at different frequencies, which is a result of the different positions and configurations of the



Sl. 5. *Vpliv obremenitve ventilatorja na spekter hrupa pri 4000 min^{-1}*
a) pri ventilatorju s premerom Ø 400 mm, b) pri ventilatorju s premerom Ø 360 mm

Fig. 5. *Influence of fan load on the noise spectrum at 4000 RPM*
a) at the fan with Ø 400 mm diameter, b) at fan with Ø 360 mm diameter

frekvencah, kar je posledica razlik v legah in zgradbi rotorskih in vodilnih lopatic ter celotnega sistema. Spektri hrupa so podobni pri vseh pretokih $Q \geqq Q_{des}$ vse do računske točke z η_{max}, pri kateri je najnižja raven hrupa L_{pmin}.

Z nadaljnjim povečevanjem dušenja se, pri $Q < Q_{des}$, zaradi pojava rotirajočih zastojnih vrtincev, spreminja širokopasoven oz. nerotirajoči hrup, zlasti v območju nizkih frekvenc. Levo od točke najmanjšega hrupa in neposredno pred mejo črpanja, med Q_{des} in $Q_{S.P.}$ na slikah 1 in 5, ko nastajajo dvoceličnі zastojni vrtinci (i = 2), nastaja hrup z izrazitim vrhom pri frekvenci med prvim in drugim harmonikom FVRL. Pri ventilatorju s premerom Ø 400 mm je to pri frekvenci med 1008 in 1136 Hz (srednja vrednost 1072 Hz) in pri ventilatorju s premerom Ø 360 mm med 976 in 1136 Hz (srednja vrednost 1056 Hz), gl. spekter i = 2 na sl. 5.

Na meji črpanja in levo od nje (glej spektre na sliki 5 pri $Q \leqq Q_{S.P.}$) lahko opazimo izrazit vrh širokopasovnega spektra hrupa pri frekvenci, ki je manjša od FVRL. Ta vrh je posledica nastajanja enoceličnega vrtinca (i = 1), ki se pojavi pri frekvenci, ki je približno polovična vrednost frekvence vrha dvoceličnega vrtinca. Ta frekvenca pri ventilatorju s premerom Ø 400 mm niha med 496 in 592 Hz (srednja vrednost 544 Hz) in pri ventilatorju Ø 360 mm med 528 in 544 Hz (srednja vrednost 536 Hz). Ker se rotirajoči spekter hrupa z dušenjem ne spreminja, nerotirajoči spekter hrupa postopoma prekriva rotirajočega, dokler ga ta v celoti ne prekrije. To se zgodi še zlasti pri zaprtem dušilnem ventilu pri $Q \cong 0$ (glej zgornje spektre na sliki 5).

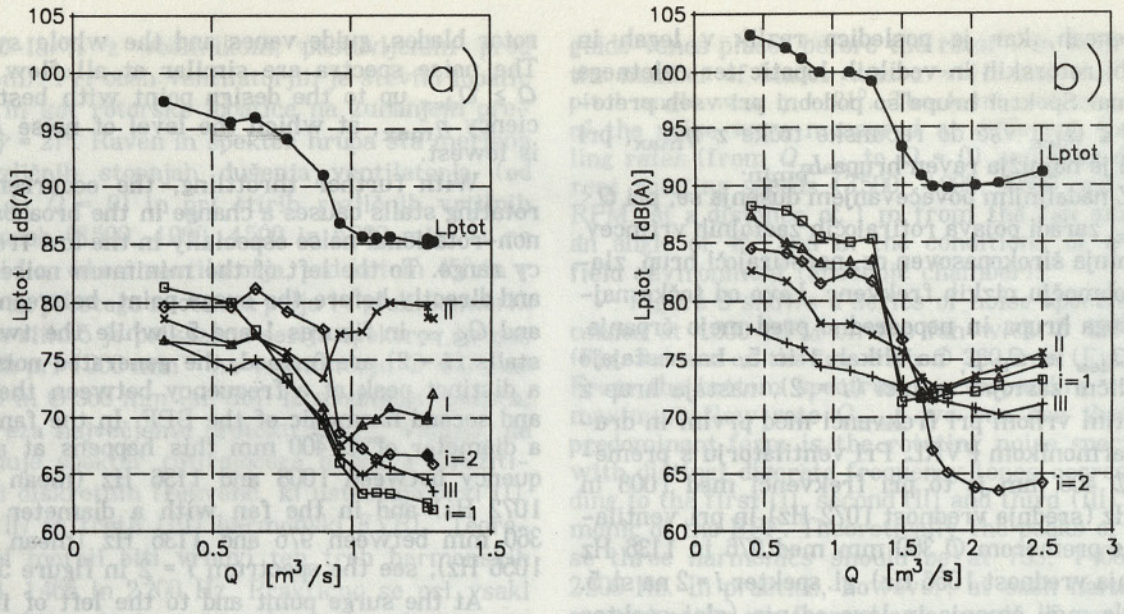
Na sliki 6 je prikazana celotna raven hrupa (L_{ptot}) in raven hrupa pri prvi (I), drugi (II) in tretji (III) harmonski FVRL ter pri frekvenci eno- (i = 1) in dvoceličnega (i = 2) vrtinca v odvisnosti od pretoka Q. S slike 6 vidimo, da se celotna raven hrupa (L_{ptot}) najprej z dušenjem postopoma niža in nato strmo veča zaradi prispevka nerotirajočega spektra hrupa. Strmo povečanje hrupa levo od najmanjše ravni hrupa in $Q < Q_{des}$ je v prvi vrsti posledica pojava zastojnih vrtincev in v manjši meri interakcije rotorskih lopatic z vrtinci v špranji med vrhom lopatice in cevjo. Višja raven hrupa pri pretoku $Q > Q_{des}$ pa je posledica nerotirajočega hrupa zaradi razkrajanja vrtincev v laminarni mejni plasti na repu lopatic rotorja [1], [2]. Pri močnem dušenju, pri $Q \cong 0$, širokopasovni nerotirajoči hrup doseže takšno raven, da v celoti prekrije tonalni rotirajoči hrup. S slike 6 vidimo tudi, da raven nerotirajočega hrupa začne strmo naraščati šele v bližini meje črpanja (glej krivulji i = 1 in i = 2). Pri ventilatorju Ø 400 mm se poveča vrh hrupa pri enoceličnem vrtincu (i = 1) s srednjo frekvenco ~ 544 Hz

rotor blades, guide vanes and the whole system. The noise spectra are similar at all flow rates $Q \geqq Q_{des}$ up to the design point with best efficiency η_{max}, at which the level of noise L_{pmin} is lowest.

With further throttling, the occurrence of rotating stalls causes a change in the broadband or non-rotational noise especially in the low frequency range. To the left of the minimum noise point and directly before the surge point, between Q_{des} and $Q_{S.P.}$ in figures 1 and 5, while the two-cell stalls (i = 2) are formed, the generated noise has a distinct peak at a frequency between the first and second harmonic of the BPF. In the fan with a diameter of Ø 400 mm this happens at a frequency between 1008 and 1136 Hz (mean value 1072 Hz) and in the fan with a diameter of Ø 360 mm between 976 and 1136 Hz (mean value 1056 Hz), see the spectrum i = 2 in figure 5.

At the surge point and to the left of it (see spectra in Fig. 5 at $Q \leqq Q_{S.P.}$) we can note a distinct peak of broadband noise spectrum at a frequency lower than the BPF. This peak is a result of the formation of a one-cell stall (i = 1), occurring at a frequency which is approximately half the frequency of the two-cell stall peak. In the fan with a diameter of Ø 400 mm this frequency ranges between 496 and 592 Hz (average value 544 Hz) and with a diameter of Ø 360 mm between 528 and 544 Hz (average value 536 Hz). Since the rotational noise spectrum is not changed by fan throttling, the non-rotational noise spectrum gradually starts overlapping the rotational noise until it overlaps the latter completely. This is especially the case at a closed throttle at $Q \cong 0$ (see the above spectra in Fig. 5).

Figure 6 shows the total noise level (L_{ptot}) and the noise level at the first (I), second (II) and third (III) harmonic of the BPF and at the frequency of one-cell (i = 1) and two-cell (i = 2) stall versus the flow rate Q. From the figure we can see that, at first throttling, the total noise level (L_{ptot}) gradually falls and then steeply increases due to the contribution of the non rotational noise spectrum. The steep increase left of the minimum noise level and at $Q < Q_{des}$ is primarily caused by the occurrence of stalls, and only in the second place by the interaction between the rotor blades with the tip clearance vortex. A higher noise level at the flow rate $Q > Q_{des}$ is a result of non-rotational noise due to the laminar boundary layer vortex shedding on the blade trailing edge [1], [2]. In very intensive throttling, at $Q \cong 0$, the broadband non-rotational noise reaches such a level that it entirely overlaps the tonal rotational noise. From figure 6 we can see that the non-rotational noise level starts increasing steeply only when close to the surge point (see curves i = 1 and i = 2). In the Ø 400 mm fan, the noise spectrum peak for the one-cell stall (i = 1) with the average frequency ~ 544 Hz is higher by 17 dB(A), and in two-cell



Sl. 6. *Raven vrhov hrupa pri karakterističnih frekvencah v odvisnosti od pretoka Q, pri n = 4000 min*$^{-1}$
a) ventilator Ø 400 mm, b) ventilator Ø 360 mm
Raven hrupa: ⊙ totalna raven (L_{ptot}), ⌗ pri frekvenci enoceličnega vrtinca (i = 1), ⊗ pri frekvenci dvoceličnega vrtinca (i = 2), Δ pri frekvenci prve harmonske (I), × pri frekvenci druge harmonske (II), + pri frekvenci tretje harmonske (III)

Fig. 6. *Noise level of the characteristic discrete frequency peaks versus flow rate Q at n = 4000 RPM*
a) at the fan with Ø 400 mm diameter, b) at the fan with Ø 360 mm diameter
Noise level: ● total noise level (L_{ptot}), ❑ at frequency of one cell stall (i = 1), ◇ at frequency of two cell stalls (i = 2), Δ at frequency of first harmonic of BPF (I), × at frequency of second harmonic of BPF (II), + at frequency of third harmonic of BPF (III)

za 17 dB(A) in pri dvoceličnem vrtincu (i = 2) s srednjo frekvenco ~ 1072 Hz za 15 dB(A). Pri tem se poveča celotna raven hrupa za okoli 10 dB(A).

Pri ventilatorju Ø 360 mm se poveča vrh hrupa pri enoceličnem vrtincu (i = 1) s srednjo frekvenco 536 Hz za 14 dB(A) in pri dvoceličnem vrtincu (i = 2) s srednjo frekvenco ~ 1056 Hz za 18 dB(A). Pri tem se poveča celotna raven hrupa za okoli 10 dB(A), kar je enako kakor pri ventilatorju Ø 400 mm. Relativni nivoji vsakega od vrhov nerotirajočega spektra hrupa naraščajo z dušenjem oz. zmanjševanjem pretokov. Frekvenca, pri kateri se pojavljajo vrhovi nerotirajočega hrupa pa se malenkostno spreminja, odvisno od obratovalnih razmer in resonance sistema. Ravni hrupa prvega, drugega in tretjega harmonika FVRL bi morale ostati teoretično nespremenjene; njihovo povečanje na sliki 6 proti manjšim pretokom je posledica prekrivanja z nerotirajočim hrupom.

Izraziti vrhovi nerotirajočega hrupa se torej pojavijo pri diskretnih frekvencah, ki ustrezajo številu celic rotirajočega vrtinca i = 1 in i = 2 ter njihovi hitrosti rotacije, ustrezno enačbi (3). Vrednost koeficienta ξ se spreminja s spremembo obratovalnih razmer, tako s spremembo vrtljajev kakor tudi obremenitve oz. dušenja. Na koeficient

stall (i = 2) with the average frequency ~1072 Hz higher by 15 dB(A). The total noise level thus grows by approximately 10 dB(A).

In the Ø 360 mm fan, the noise spectrum peak increases for the one-cell stall (i = 1) with an average frequency ~536 Hz by 14 dB(A) and for the two-cell stall (i = 2) with an average frequency of ~ 1056 Hz by 18 dB(A). The total noise level increases thus by approximately 10 dB(A), which is by the same amount as in the Ø 400 mm fan. The relative levels of each of the non-rotational noise spectrum peaks grow with throttling or reducing the flow rates. The frequency at which non-rotational noise peaks occur is subject to slight changes depending on the operating conditions and resonance of the system. The noise levels of the first, second and third harmonic of the BPF should theoretically remain the same, their increase (see Fig. 6), versus smaller flow rates being a result of overlapping with the non-rotational noise.

Distinct peaks of non-rotational noise thus occur at discrete frequencies which correspond to the number of rotational stall cells i = 1 and i = = 2, and the speed of their rotation in accordance with equation (3). The value of the coefficient ξ changes with altered operating conditions, and

ξ vplivajo poleg spremembe obratovalnih razmer tudi lega vodilnih lopatic, ki so lahko pred rotorjem ali za njim, ter zgradba sistema. S spremembo vrtilnih frekvenc in obremenitve ter pri različnih legah vodilnih lopatic vrednosti koeficienta ξ nihajo v mejah med 0,60 in 0,84. Srednja vrednost koeficienta ξ je potem ~ 0,72. Iz tega izhaja, da se vrh enoceličnega vrtinca (i = 1) pojavlja pri neki srednji frekvenci ~ 0,72 · FVRL in vrh hrupa dvoceličnega vrtinca (i = 2) pri ~ 1,44 · FVRL.

4 SKLEP

Meja črpanja pomeni ločnico med stabilnim in nestabilnim delom karakteristike ventilatorja ozirma spodnjo mejo uporabnosti ventilatorja. Meja črpanja nastane zaradi nastajanja zastojnih vrtincev pri delnih obremenitvah, pri $Q_{S.P.} = Q < Q_{des}$. Pri tem pride do padca tlaka, pretoka in izkoristka. Pride tudi do strmega porasta nerotirajočega spektra hrupa, ki ima dva karakteristična vrha. Prvi vrh, ki ustreza enoceličnemu zastojnemu vrtincu (i =1), se pojavlja pri ~ 0,72 · FVRL. Drugi vrh, ki ustreza dvoceličnemu zastojnemu vrtincu (i = 2), se pojavlja pri ~1,44 · FVRL ali pri dvakratni vrednosti vrha enoceličnega vrtinca. Frekvence, pri katerih se pojavljata vrha nerotirajočega spektra hrupa in njuni amplitudi se malenkostno spreminjajo z obratovalnimi razmerami in konfiguracijo sistema, vendar značaj in pomen vrhov v spektru ostaja skoraj nespremenjen. Frekvence vrhov nerotirajočega hrupa z i =1 in i = 2 lahko izračunamo z uporabo enačbe (3).

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hence with the change in the number of revolutions as well as loads or fan throttling. The coefficient ξ is also affected by the position of the guide vanes either before or behind the rotor and the given fan configuration. With a change in the number of revolutions and loads, and at different guide vanes positions, the value of the coefficient ξ varies within 0.60 and 0.84. The mean value of the coefficient ξ is then ~ 0.72. From this it follows that the peak of a one-cell stall (i = 1) occurs at an average frequency ~ 0.72 · BPF and the peak of a two-cell stall (i = 2) at ~ ~ 1.44 · BPF.

CONCLUSION

The surge point presents a borderline between the stable and unstable part of a given fan's characteristics, i.e. the lower limit of usefulness of the fan. The surge point occurs as a result of stall formation at partial loads, at $Q_{S.P.} = Q < Q_{des}$. This results in a drastic drop in pressure, flow rate and efficiency. There also occurs a steep increase in the non-rotational noise spectrum, which has two characteristic peaks. The first peak, corresponding to a one-cell stall (i = 1), occurs at ~ 0.72 · BPF, while the second peak corresponding to a two-cell stall (i = 2) occurs at ~ 1.44 · BPF, or at twice the value of the one-cell stall. The frequencies at which the peaks of the non-rotational noise spectrum occur, and their amplitudes, vary slightly with operating conditions and a given configuration, yet the characteristic and significance of the peaks remain the same. The frequencies of the non-rotational noise peaks with i = 1 and i = 2 can be calculated by means of equation (3).

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