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Razvoj metodologije za zaštitu od industrijske buke na primeru sistema za otprašivanje livnice

Branko Radičević[1], Mišo Bjelić[*1], Mile Savković[1], Nebojša Zdravković[1], Aleksandra Petrović[1]
[1] Fakultet za mašinstvo i građevinarstvo u Kraljevu, Univerzitet u Kragujevcu, Srbija

U radu je prikazan razvoj metodologije za zaštitu od buke na primeru sistema za otprašivanje livnice. Razvijena metodologija za zaštitu od buke polazi od činjenice da su moguća mesta zvučne zaštite na samom izvoru zvuka, na putevima prostiranja zvučnih talasa i na mestu prijema. Osnovu metodologije za rešavanje konkretnih primera zaštite od buke čini model za prognozu buke, koji se sastoji iz dva osnovna dela, modela izvora i modela prostiranja buke. Izlaz iz modela je polje buke, na osnovu koga se izrađuje mapa buke.

Na konkretnom primeru, definisane su aktivnosti u postupku zaštite od buke i utvrđena njihova međuzavisnost. Projektovanje sistema zaštite od buke podrazumeva uzimanje u obzir niza funkcionalnih, tehnoloških i drugih ograničenja. Na osnovu potrebnog smanjenja nivoa buke od 15 dB u najbližoj stambenoj jedinici, formirana su varijantna rešenja zaštite od buke. Izbor konačnog rešenja za zaštitu od buke ventilacionog sistema livnice je izvršen na osnovu tehno-ekonomske analize.

Keywords: industrijska buka, model za prognozu buke, sistem za otprašivanje, zvučna apsorpcija

1. UVOD

Savremena tehnologija livenja i moderna oprema omogućavaju dobijanje odlivaka koji imaju široko područje primene. Većinu tehnoloških operacija livenja karakteriše velika zaprašenost vazduha, zbog čega je potrebno obezbediti otprašivanje livnice. Otprašivanje tehnoloških linija postrojenja livnice i livačkih peći može se izvesti centralizovano ili parcijalno za svaku tehnološku celinu. Čest način realizacije sistema za otprašivanje livnica sastoji se od dve nezavisne celine. Prvu celinu čini linija tehnoloških postrojenja, a drugu celinu livačke peći. Na ovakav način je rešen sistem za otprašivanje livnice koji je prikazan u ovom radu.

Svaki od ovih sistema otprašivanja je rešen sa jednim centrifugalnim ventilatorom koji pomoću usisnih hauba i cevovoda dovodi zaprašen vazduh u vrećasti filter. Otprašivanje se sprovodi suvim postupkom pomoću vrećastih filtara sa pneumatskim otresanjem. Prašina se prikuplja u bunkerima i prebacuje u kontejnere ispod filtra, koji se periodično prazne. Ovakvi sistemi su po pravilu velikih gabarita i postavljaju se pored proizvodnih hala, tako da predstavljaju generatore buke u životnoj sredini.

Projektovanje sistema za zaštitu od buke sistema za otprašivanje je veoma složen zadatak. Zbog toga je potrebno razviti metodologiju za rešavanje takvih problema. U procesu projektovanja zvučne zaštite veoma je važno poznavati funkcije sistema. Na putu rešenja problema zaštite od buke često stoje tehnološki zahtevi, izvedene instalacije, način vezivanja elemenata zaštite i drugi uticajni faktori.

Ovaj rad se odnosi na realizovanu zaštitu od buke na konkretnom primeru sistema za otprašivanje livnice. Na osnovu analize postojeće situacije evidentirano je prekoračenje graničnih vrednosti nivoa buke u životnoj sredini. Pri maksimalnom režimu rada livnice, merenjem u najbližoj stambenoj jedinici utvrđeno je prekoračenje nivoa buke od 15 dB. Projektovane su i sprovedene mere zvučne zaštite na samim izvorima. Razmatrana je mogućnost izgradnje zvučnih barijera na putu prenošenja zvučnih talasa, ali obzirom na konfiguraciju terena takvo rešenje nije efektivno. Primenom metodološkog pristupa koji je prikazan u ovom radu, nivo buke u prostoriji u kojoj je evidentirano prekoračenje je sveden na 30 dB. Merama zvučne zaštite ostvarena je zakonom utvrđena granična vrednost indikatora buke u toku noćnog perioda u zatvorenom prostoru u životnoj sredini.

2. ANALIZA PROBLEMA

Filtersko postrojenje za otprašivanje livnice je velikih dimenzija. Uzimajuću u obzir i dužinu cevovoda filtersko postrojenje za otprašivanje tehnoloških linija livnice je dugačko oko 22 m, slika 1.a. Telo vrećastog filtera je dužine 8 m i visine 9 m. Visina dimnjaka je iznosila oko 11 m. Brzina strujanja vazduha u cevovodima na osnovu uvida u tehničku dokumentaciju [16] iznosi 23 m/s. Snaga centrifugalnog ventilatora je 125 kW, a snaga njegovog pogonskog elektromotora 132 kW. Filtersko postrojenje je postavljeno pored proizvodnog pogona livnice u čijem neposrenom okruženju se nalazi stambeno naselje. Najbliža stambena jedinica je udaljena oko 40 m od sredine filterskog postrojenja. Pri svom radu sistem za otprašivanje generiše visok nivo buke koji prekoračuje granične vrednosti indikatora buke u životnoj sredini. U daljim analizama navedeno filtersko postrojenje je označeno kao filter F1.

Drugo filtersko postrojenje, slika 1.b, služi za otprašivanje livačkih peći. Manjih je dimenzija u odnosu na filter F1 i nalazi se na većoj udaljenosti u odnosu na stambeno naselje. Brzina strujanja vazduha u cevovodima iznosi 20 m/s. Snaga centrifugalnog ventilatora je 55 kW, a snaga njegovog pogonskog elektromotora 75 kW. U daljim analizama navedeno filtersko postrojenje je označeno kao filter F2.

U odnosu na nivo buke zvučnih izvora, pored filterskih postrojenja u kategoriju dominantnih zvučnih izvora spadaju i rashladne kule. U odnosu na stambeno naselje rashladne kule su u potpunosti zaklonjene visokim proizvodnim pogonom livnice, koji praktično predstavlja zvuč-

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*Kontakt adresa autora: Dositejeva 19, 36000 Kraljevo, bjelic.m@mfkv.kg.ac.rs

nu barijeru za prostiranje buke od ovih zvučnih izvora. Buka peskare i buka viljuškara ispred proizvodnog pogona imaju uticaj na nivoe buke u stambenom naselju koje je ugroženo bukom. Mala ulica koja prolazi sa druge strane stambenog naselja ima neznatni uticaj na nivo buke na mernim mestima koja su odabrana za ocenu buke koju generiše livnica.

a)

b)

Slika 1. Dominantni izvori buke u livnici: a) Filter F1, b) Filter F2

3. RAZVOJ METODOLOGIJE ZA ZAŠTITU OD BUKE INDUSTRIJSKIH IZVORA

Imajući u vidu osnovne mehanizme generisanja zvučne energije kod industrijskih izvora koji mogu biti mehanički, aerodinamički i magnetni [10-12], i moguće principe kontrole buke, na samom zvučnom izvoru, na putu prostiranja zvučnih talasa i na mestu prijemnika, moguće je razviti veliki broj varijantnih rešenja za zaštitu od buke industrijskih postrojenja. Zbog toga je potrebno razviti metodologiju koja će služiti kao smernica za implementaciju znanja iz ove oblasti.

Za realizaciju sistema zaštite od buke može se koristiti metodologija koja se sastoji od sledećih faza:

- Analiza postojećeg stanja
- Formiranje modela za prognozu buke
- Izbor varijantnih rešenja u cilju promene karaktera buke
- Izbor parametara i neki očekivani efekti pri projektovanju elemenata zvučne zaštite
- Izrada i montaža elemenata zvučne zaštite
- Merenje nivoa buke i verifikacija sistema zvučne zaštite

3.1. Analiza postojećeg stanja

Analiza postojećeg stanja započinje analizom buke u životnoj sredini koja je uzrokovana industrijskom bukom. Ukoliko na mestu prijemnika u životnoj sredini postoji uticaj i drugih zvučnih izvora, kao što je na primer saobraćaj ili neki drugi izvor, potrebno je odrediti specifični uticaj buke industrijskih postrojenja. Nivo buke u životnoj sredini sme prekoračiti granične vrednosti indikatora buke koji su zakonom definisani. Nivo buke iznad graničnih vrednosti remeti odmor, spavanje i radne aktivnosti ljudi.

Analiza postojećeg stanja zvučnih izvora započinje sa upoznavanjem funkcijama i tehnološkim parametrima mašina, opreme, uređaja i postrojenja, čiju zvučnu zaštitu treba realizovati. Kontrola buke na samom izvoru spada u kategoriju primarnih mera. Njihovom realizacijom često se eliminiše potreba za primenom mera na putu prenošenja zvučnih talasa ili na mestu prijemnika. U početnoj analizi zvučnih izvora potrebno je identifikovati sve izvore buke i odrediti glavne mehanizme generisanja zvučne energije. Za lociranje dominantnih zvučnih izvora najefikasnija je metoda intenziteta zvuka, jer se njenom primenom može isključiti buka drugih izvora. Pozadinska buka je najčešći poremećajni faktor kada je primena drugih metoda u pitanju.

Kod merenja industrijske buke najčešće postoji mnoštvo zvučnih izvora sa različitim načinima generisanja zvučne energije. U takvoj situaciji, za identifikaciju zvučnih izvora može se koristiti i metoda merenja zvučnog pritiska. Kod primene ove metode najvažnije je odrediti rastojanje mikrofona od zvučnog izvora. Rastojanje zavisi od načina kojim zvučni izvori predaju energiju elastičnoj sredini. Mehanizmi nastajanja zvučnih talasa mogu biti: vibriranje površina krutih tela, prinudno pulsiranje vazdušne struje, turbulencija u fluidima i brza termička dejstva. Da bi se izbegao uticaj drugih zvučnih izvora, iskustva sa nekih od realizovanih projekata zaštite od buke [2-9] su pokazala da je mikrofon najbolje postaviti neposredno uz zvučni izvor, ili na rastojanje koje nije veće od 0,5 m od njega. Treba imati u vidu, da se radi o merenju zvučnog pritiska u bliskom polju koje zavisi od oblika izvora. Zbog navedenih uticaja, potrebno je izmerenu vrednost zvučnog pritiska u bliskom pollju korigovati. Iskustveno je utvrđeno umanjenje zvučnog pritiska od 3 dB do 6 dB u zavisnosti od mehanizma nastajanja zvuka.

3.2. Formiranje modela za prognozu buke

Modeli za prognozu buke su najčešće realizovani kao dvodelni. Prvi deo predstavlja model izvora buke a drugi deo model prostiranja buke. Ovakvi modeli često mogu zameniti terenska merenja, koja nekada zbog ograničavajućih faktora nije moguće sprovesti. Izračunavanje nivoa buke na ovakav način je posebno značajno za slučajeve: visoke pozadinske buke, izrade planske dokumentacije, razvoja alternativa za zaštitu od buke i izrade konturnih mapa buke. Primena ovakvih modela omogućava detaljne informacije o velikom broju zvučnih izvora i njihovom pojedinačnom ili zbirnom uticaju na nivo buke na mestu prijemnika. Ovakva metodologija omogućava ocenu različitih hipotetičkih situacija. Za razliku od realnih merenja može se eliminisati pozadinska buka i uticaj meteoroloških parametara. Nedostaci primene ovakve metodologije ogledaju se u velikom broju potrebnih informacija o topografiji terena, geometriji i dimenzijama objekata koji predstavljaju zvučne barijere. Takođe je potrebno poznavati dimenzije zvučnih izvora i specifične nivoe buke koju oni generišu. Posebno je važan podatak o visini akustičkog centra zvučnog izvora, ukoliko je on modeliran kao tačkast. Tačnost rezultata u mnogome zavisi od iskustva i veštine osobe koja koristi model.

Razvijeni su mnogobrojni nacionalni i međunarodni standardi koji definišu algoritam modela za prognozu buke. Algoritmi su empirijske prirode i bazirani su na zavisnostima prostiranja buke. Mnogi od ovih modela se mogu primeniti korišćenjem jednostavnih izračunavanja, kada je u pitanju jedan ili mali broj izvora. Potreba da se nivo buke određuje u velikom broju tačaka i da se istovremeno posmatra veliki broj zvučnih izvora, dovela je do potrebe primene računara. Na taj način omogućeno je brže izračunavanje, analiza i prezentacija rezultata u različitim formatima. Najčešći način prikazivanja izlaznih rezultata je prikazivanje nivoa buke u čvorovima mreže koja obuhvata prostor u kome se želi analizirati nivo buke. Na osnovu rezultata nivoa buke u čvornim tačkama mreže formira se konturna mapa buke, koja predstavlja vizuelizaciju polja buke. Algoritmi su najčešće orijentisani ka određenom tipu izvora, što ograničava mogućnost njihove primene. Izuzetak predstavlja metoda definisana standardom ISO 9613, koja se može primeniti na bilo koji izvor za koji je poznat podatak o nivou zvučne snage.

Osnovni problem pri proračunu mapa buke predstavlja model prostiranja buke. Približne formule koje se koriste u inženjerskim modelima su izvedene pod određenim ograničenjima, pa zato njiihova primena zahteva pažljivo korišćenje ulaznih podataka. Softver za proračun lokalnih mapa buke [1] omogućava proračun polja buke koje stvara veliki broj tačkastih izvora. Proračunom se može analizirati uticaj postojećih i željenih linijske barijere na nivo buke na mestu prijemnika. Polje buke je predstavljeno vrednostima nivoa buke u čvorovima trodimenzionalne mreže. Mreža se formira sa željenim korakom po tri međusobno upravne koordinatne ose. Najjednostavniji je slučaj terena koji je ravan i horizontalan, odnosno nema visinske razlike između prostora na kome su smešteni zvučni izvori i prijemnik. Zadavanjem visine definiše se položaj pojedinačne čvorne tačke a time i položaj ravni u kojoj se nalazi polje buke koje je paralelno sa podlogom. Ako je teren neravan potrebno je poznavati izohipse terena. Pored vrednosti nivoa buke u čvornim tačkama mreže, moguće je izračunati nivo buke u izabranim karakterističnim tačkama u prostoru, takozvanim kontrolnim tačkama.

Proračun polja buke zasniva se na standardu ISO 9613 [13], prema modifikacijama usvojenim u domaćoj praksi [1]. Pri proračunu se pretpostavlja da izvori buke nemaju izraženu direktivnost i da su sve barijere mnogo šire od talasne dužine zvuka, tako da se difrakcija može zanemariti. Pod navedenim pretpostavkama, nivo buke u prijemnoj tački (L) se može izračunati prema izrazu (1):

$$L = L_w + C \tag{1}$$

gde su: Lw - nivo zvučne snage izvora, C - korekcija nivoa zvuka koja se u primenjenom modelu može izraziti zbirom (2):

$$C = C_{DA} + C_G + C_B \tag{2}$$

gde su: C_{DA} – korekcija koja nastaje usled širenja talasnog fronta i apsorpcije u vazduhu, C_G – korekcija apsorpcije terena, C_B – korekcija zbog barijere.

Vrednosti nanavedenih korekcija se izračunavaju prema izrazima (3-5):

$$C_{DA} = 11 - 20\log\left(s_\perp\right) - s_\perp/200 \;\left[dB\right] \tag{3}$$

gde je: $s_\perp$ - najkraće normalno rastojanje između izvora buke i prijemne tačke.

$$C_G = \frac{h_m}{d}\left(34 + \frac{600}{d}\right) - 4.8 \;\left[dB\right] \tag{4}$$

gde su: h_m - srednja visina linije koja spaja izvor buke i prijemnu tačku, d - dužina te linije.

Korekcija zbog barijere se izračunava prema izrazu:

$$C_B = -7\log\left(5 + \frac{70 + 0.25 s_\perp}{1 + 0.2 s_\perp}\right) z_\perp K_{w\perp}^2 \;\left[dB\right] \tag{5}$$

gde je: $z_\perp$ - razlika puteva difraktovanog i direktnog talasa izražena formulom (6):

$$z_\perp = A_\perp + B_\perp + C_\perp - s_\perp \tag{6}$$

gde su: $A_\perp$ - rastojanje od izvora do gornje ivice barijere, - rastojanje od prijemnika do gornje ivice barijere, $B_\perp$ - suma dužina prelomnih ivica kod barijera sa više prelomnih ivica. Meteorološka korekcija $K_{w\perp}$ u izrazu (5) se određuje prema formuli (7):

$$K_{w\perp} = \exp\left(-\frac{1}{200}\sqrt{\frac{A_\perp B_\perp s_\perp}{2 z_\perp}}\right) \;\left[dB\right] \tag{7}$$

Navedeni postupak proračuna je pre svega pogodan kada se na mestu prijemnika određuje nivo buke koji potiče od velikog broja tačkastih izvora. Zbog toga se može pretpostaviti da takvi izvori formiraju složeni neperiodični zvuk. Spektralne komponente složenog zvuka imaju različite jednako verovatne fazne stavove na mestu prijemnika, tako da se ukupni nivo zvuka na mestu prijemnika može izračunati prema izrazu (8):

$$L_{Aeq,R} = 10\log\sum_{i=1}^{N} 10^{0.1 L_{Aeq,i}} \tag{8}$$

gde su : $L_{Aeq,i}$ - ниво буке i - tog izvora dobijen primenom A - težinske krive, N - ukupan broj zvučnih izvora.

Prema veličini prekoračenja nivoa buke na mestu prijemnika, ona se mogu klasifikovati na sledeći način: manja (do 2 dB), srednja (2÷5 dB), velika (6÷10 dB) i veoma velika (> 10 dB).

3.3. Izbor varijantnih rešenja i promena karaktera buke

Pri projektovanju i proizvodnji tehnoloških sistema koji su potencijalni izvori buke, mogu se koristiti metode koje će obezbediti tiši rad. Ova problematika je definisana međunarodnim standardima, direktivama i drugim zakonskim aktima, koji daju smernice za kontrolu buke na određenim vrstama zvučnih izvora. Posebno oštre zahteve po pitanju emisije buke ima oprema koja radi na otvorenom prostoru i može da ugrožava životnu sredinu. Naše zakonodavstvo pokriva ovu oblast Pravilnikom o buci koji emituje oprema koja se upotrebljava na otvorenom prostoru (“Sl. glasnik RS”, br. 1/2013). Pored projektovanja i izrade opreme, održavanje opreme može bitno da utiče na nivo buke koji ona generiše.

Prilikom projektovanja, rekonstrukcije i održavanja opreme treba se pridržavati nekoliko osnovnih principa redukcije buke. Atmosfera je dobar visokofrekvencijski filter. Zbog toga frekvencijski sadržaj buke treba pomerati ka višim frekvencijama. Ovo se može videti na primeru ventilatora, gde se sa promenom broja lopatica radnog kola može promeniti frekvencijski sadržaj buke i bitno smanjiti zona njenog štetnog uticaja. Nagle promene fizičkih veličina koje su karakteristika kretanja ili procesa, poput sila, pritiska i brzine, utiču na generisanje buke na višim frekvencijama. Brzina ponavljanja promene sile ili pritiska određuje frekvencijski sadržaj tako što duži interval ponavljanja stvara niskofrekvencijsku buku i obrnuto. Veća elastičnost kontaktnih površina utiče na povećanje dužine trajanja kontakta, čime se generiše buka sa nižim frekvencijskim sadržajem. Smanjenje površine velikih ploča koje su pobuđene vibracijama, značajno utiče na smanjenje nivoa generisane buke. Više dugih i uskih pokretnih elemenata generišu niži nivo buke u odnosu na jedan element iste ukupne površine. Dodavanjem slojeva sa visokim koeficijentom prigušenja vibracija na metalne površine, može se smanjiti nivo njihove generisane zvučne energije. Izbor spojeva ploča sa slobodnim krajevima sprečava nastajanje buke na niskim frekvencijama. Ako izvor buke vibrira i pri tome je oslonjen ili vezan za elemente građevinske konstrukcije, dolazi do generisanja strukturnog zvuka. Rešavanje ovog problema se može izvesti izolacijom vibracija pomoću elastičnih podloga i opruga ili izgradnjom temelja za oslanjanje mašina.

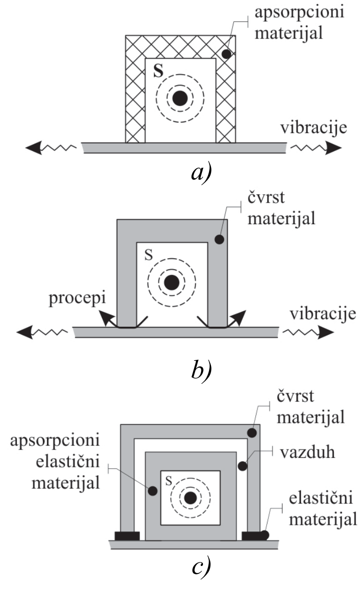
Kada nije moguće izvesti zvučnu zaštitu samog izvora primenjuju se mere kontrole na putevima prenošenja zvučnih talasa. Kontrola vazdušne buke na putu prostiranja zvučnih talasa moguće je ostvariti oklapanjem izvora, postavljanjem barijera ili tunela između izvora i prijemnika. Primenom apsorpcionih komora smanjuje se uticaj reflektovanih talasa, a samim tim i generisanje ukupnog nivoa buke u okruženje. Oklapanje izvora se izvodi na više različitih načina. Zvučni izvor se može oklopiti apsorpcionim materijalom, čvrstim materijalom ili oklopima sa više slojeva. Barijere se postavljaju na putu prostiranja zvučnih talasa od izvora do prijemnika, a redukciju nivoa buke vrše sprečavanjem prostiranja zvučnih talasa. Da bi barijera imala punu efektivnost mora se sprečiti direktna vidljivost prijemnika sa pozicije izvora.

3.4. Izbor parametara i neki očekivani efekti pri projektovanju elemenata zvučne zaštite

Mašine i postrojenja koje se koriste u industriji spadaju u grupu stacionarnih izvora čiji nivo buke zavisi od instalisane snage. Mašinsku opremu koja se koristi u industrijskim pogonima čine: elektromotori, motori sa unutrašnjim sagorevanjem, pumpe, ventilatori, kompresori, transformatori, generatori, transporteri, reduktori, rashladne kule, ventilacioni sistemi i sl. Glavni mehanizmi generisanja buke mogu se podeliti u tri grupe: mehanički, aerodinamički i magnetni. Mehanički mehanizmi generisanja buke kao što su debalans, nesaosnost, odstupanja od oblika i položaja, mogu se uspešno rešiti praćenjem stanja i primenom metoda preventivnog održavanja. Nepravilno održavanje može dovesti do povećanja nivoa buke i do 20 dB(A)[10]. Mašinska oprema generiše visoke nivoe buke srednjih i visokih frekvencija. Frekvencijske komponente buke su proporcionalne rotacionoj brzini mašinskih elemenata. Rad elektičnih mašina karateriše postojanje elektromagnetnih i mehaničkih sila, usled čega nastaju vibracije elemenata i površina ovih mašina, što za posledicu ima generisanje buke.

Aerodinamička buka nastaje kao posledica kretanja fluida i njegovog ispuštanja na mestima izvršnih organa i elemenata pneumatske instalacije. Ova buka može biti visokog nivoa ako se fluid na svom putu ima dosta usputnih i lokalnih prepreka pri čemu se javlja turbulencija, a kao rezultat toga širokopojasna buka. Pored toga javljaju se i tonalne komponente koje nastaju kao posledica presecanja fluidnog toka pomoću rotirajućih elemenata. Ako u mašinskom sistemu ima više rorirajućih komponenata, svaka od nih generiše svoj skup tonalnih komponenata. Aerodinamička buka se javlja kod pneumatskih transportera koji se koriste za transport žitarica, cementa, ugljene prašine, sitnog uglja, drvene piljevine, pepela i drugih materijala. Udaranje materijala o zidove cevi na mestima promene pravca strujanja i drugim preprekama, stvara turbulenciju vazduha, što dovodi do dodatnog povišenja nivoa buke. Pneumatski transporteri su uglavnom velike dužine, postavljeni na otvorenom prostoru, tako da predstavljaju značajan izvor buke u životnoj sredini.

Princip pneumatskog transporta je iskorišćen kod sistema za otprašivanje livnice koji je prikazan u ovom radu. Čestice prašine, peska i tehnoloških para se pomoću usisnih hauba ubacuju u cevovod, transportuju do filterskih postrojenja, odakle se prečišćen vazduh kroz dimnjak izbacuje u atmosferu. Zaštita od buke ovakvog sistema može se realizovati ako se uzmu u obzir svi mehanizmi generisanja buke i svi principi kontrole buke.



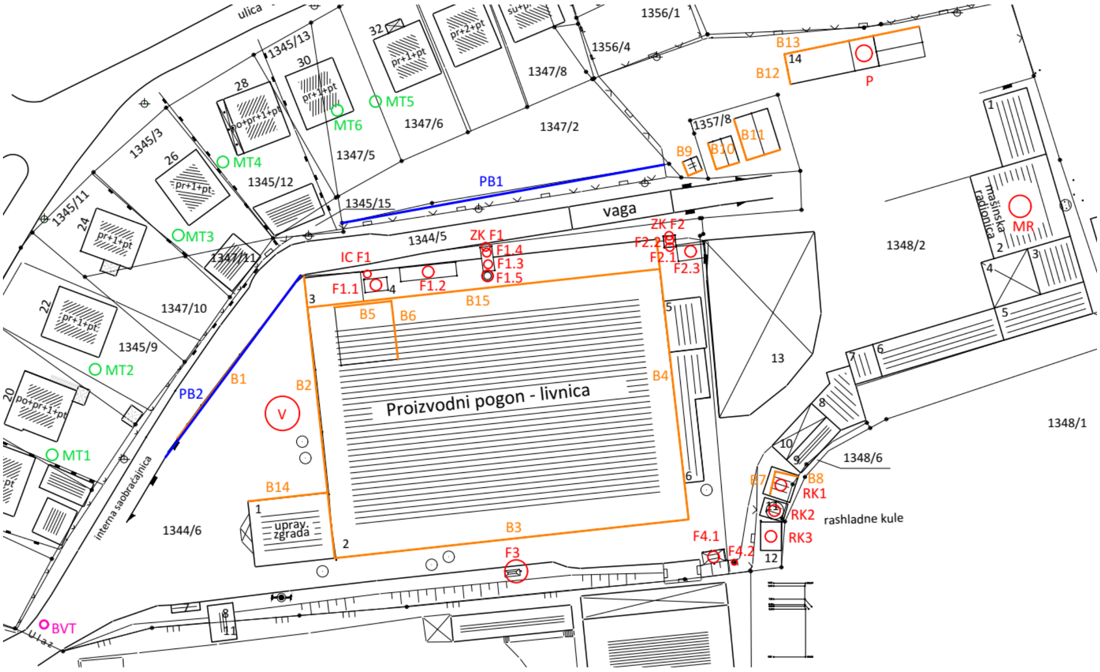
Slika 2. Vrste i očekivani efekti redukcije buke kod oklopljenih zvučnih izvora [10]

Na slici 2. prikazana su tri načina oklapanja zvučnih izvora. Značajno je istaći efekte redukcije buke svakog od navedenih rešenja [10]. Oklapanjem izvora apsorpcionim materijalom, bez presecanja puteva širenja vibracija može se ostvariti efekat smanjenja buke od 3÷5 dB, slika 2.a. Isti takav oklop od čvrstog materijala, pod istim uslovima, redukuje nivo buke u opsegu od 3÷10 dB, slika 2.b. Najefikasniji način oklapanja su oklopi sa više slojeva, kao što je prikazano na slici 2. c. Ako to uslovi dozvoljavaju, najbolje je da jedan sloj bude izrađen od apsorpcionog materijala a drugi od čvrstog materijala. Razlog za to leži u činjenici da pregrada koja ima veću masu bolje apsorbuje niske frekvencije zvučnog talasa, a apsorpcioni material bolje apsorbuje srednje i visoke frekvencije buke. Oklopi sa više slojeva od raznorodnih materijala, slika 2.c, kod kojih je širenje vibracija smanjeno pomoću elastičnih materijala, mogu dati efekat redukcije buke i preko 20 dB. Problem nastaje kada je na oklopu potrebno napraviti otvore za ventilaciju. Otvori se najčešće izrađuju zbog dopremanja svežeg vazduha za potrebe hlađenja. Bolji način za rešenje ovog problema su ventilacioni kanali koji su sa unutrašnje strane obloženi apsorpcionim materijalom.

4. REZULTATI I DISKUSIJA REALIZOVANE ZAŠTITE OD BUKE NA PRIMERU SISTEMA ZA OTPRAŠIVANJE LIVNICE

4.1. Analiza postojećeg stanja

Katastarsko-topografski plan je korišćen kao osnova za formiranje digitalnog modela terena i digitalnog modela objekata na terenu. Plan sadrži položajni i visinski prikaz terena, položaj svih objekata i prateće infrastrukture, kao i zvanične granice katastarskih parcela prostora na kome se nalazi livnica i stambeno područje koje je ugroženo bukom. Pored toga, unet je položaj svih podzemniih i nadzemnih infrastrukturnih vodova. Na osnovu tehničke dokumentacije i uvida na licu mesta, definisan je širi skup uticajnih zvučnih izvora koji generišu buku u životnoj sredini. Na osnovu nivoa zvučnog pritiska koji je utvrđen na način koji je prikazan u okviru tačke 3.1, definisani su dominantni zvučni izvori koji su navedeni u okviru analize problema (tačka 2).



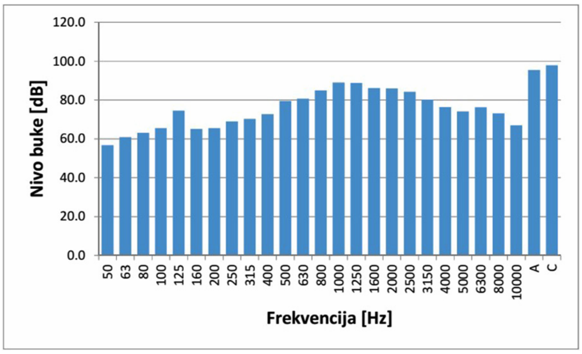
Slika 3. Položaj dominantnih zvučnih izvora, postojećih i planiranih barijera i mernih tačaka u stambenom okruženju

Na slici 3. su prikazani dominantni izvori buke livnice u životnoj sredini. Sa severne strane proizvodnog pogona nalazi se grupa izvora buke koji pripadaju podsistemima filtera F1 i F2 koji su najbliži stambenom naselju. Proizvodni pogon livnice je okružen izvorima buke: sa južne strane nalazi se filter F3, sa jugoistočne rashladne kule RK, sa istočne mašinska radionica MR, severoistočne peskara P i sa zapadne viljuškar V. Na istoj slici su prikazane postojeće barijere koje nose oznaku B. One predstavljaju zidove postojećih građevinskih objekata, koji se nalaze na putu prostiranja zvučnih talasa prema stambenom naselju. Osim postojećih prikazan je položaj planiranih barijera PB, čiji je uticaj analiziran u okviru varijantnih rešenja za zaštitu od buke. U prethodnom periodu livnica je sprovela mere zaštite od buke za oba centrifugalna ventilatora i njihove pogonske elektromotore, slika 1. Zaštita se sastojala u njihovom delimičnom oklapanju pomoću apsorpcionih panela. Ovakvo rešenje nije dalo zadovoljavajuće efekte zvučne zaštite u stambenom naselju. Razmotrena je mogućnost da se delimična zaštita integriše u sistem višeslojnog oklopa, koji je predložen i kasnije realizovan kao mera zvučne zaštite.

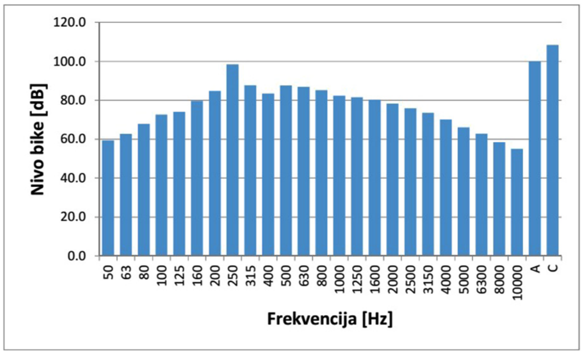
Izvršena su merenja i analize svih identifikovanih zvučnih izvora u cilju određivanja dominantnih zvučnih izvora u livnici. Skup dominantnih izvora čine izvori čiji je nivo buke za manje od 10 dB niži u odnosu na izvor sa maksimalnim nivoom zvučnog pritiska.

Merne tačke u stambenom naselju su označene sa MT. Merenjem nivoa buke na mernim tačkama, utvrđeno je da merna tačka MT5 ima najviši nivo spoljašnje buke. Ekvivalentni nivo buke na ovoj mernoj tački je iznosio 61.4 dB(A). U daljim analizama ova merna tačka je označena kao referentna za ocenu buke u čitavom stambenom naselju.

Za merenje buke u zatvorenim prostorijama odabrana je najbliža stambena jedinica pored referentne merne tačke. Merenje je izvršeno u boravišnoj prostoriji na prvom spratu koja je najisturenija prema izvorima buke. Ova merna tačka je označena sa MT6. U sredini prostorije pri zatvorenim prozorima i vratima izmeren je ekvivalentni nivo buke od 44.9 dB(A). Soba u kojoj je vršeno merenje ima relativno stari drveni prozor sa duplim krilima.

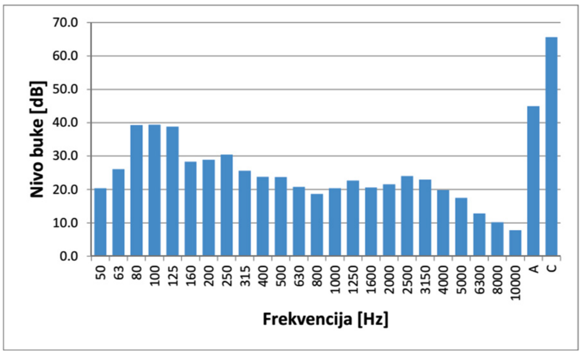


a)



b)

Slika 4. Frekvencijski spektar buke izvora sa najvišim nivoom buke: a) Frekvencijski spektar buke pogonskog motora ventilatora filtera F1 (L_{Aeq} = 95.4 dB), b) Frekvencijski spektar aerodinamičke buke na izlazu iz dimnjaka filtera F1 (L_{Aeq} = 100.0 dB)



a)

Prema standardu SRPS U.J6. 201 [15], pomenuti prozor se može svrstati u IV klasu u odnosu na izolacionu moć od 20÷24 dB.

Cilj izgradnje sistema zvučne zaštite je bio da se nivo buke na mernoj tački MT6 dovede na nivo od 30 dB(A), koji prema važećoj Uredbi ("SL. glasnik RS", br. 75/2010) predstavlja graničnu vrednost indikatora buke u zatvorenom prostoru u životnoj sredini u toku noći.

b)

Slika 5. Frekvencijski spektar buke u najugroženijoj boravišnoj prostoriji na prvom spratu kuće (MT6): a) Frekvencijski spektar buke na mernoj tački MT6, (L_{Aeq} = 44.9 dB), b) Merna tačka MT6 (udaljenost 40 m od dimnjaka filtera F1)

4.2. Prognoza buke u ugroženom stambenom naselju

Prognoza buke u stambenoj zoni ugroženoj bukom je izvršena pomoću softvera Bel-Čo koji je razvijen na Fakultetu za mašinstvo i građevinarstvo u Kraljevu Univerziteta u Kragujevcu. Softver je baziran na proračunu koji je definisan u okviru tačke 3.2 u ovom radu. Detaljan opis softvera je dat u tehničkom rešenju – Softver za proračun lokalnih mapa buke [1].

Tabela 1. Validacija mape buke na kontrolnim tačkama

Merno mesto	**Model (mapa buke) [dBA]**	**Izmerena vrednost [dBA]**	**Razlika [dBA]**
MT1	57.2	59.7	2.5
MT2	59.8	60.6	0.8
MT3	59.8	60.6	0.8
MT4	64.0	60.5	3.5
MT5	61.7	61.4	0.3

Primena softvera za proračun mapa buke je otežan kada teren nije ravan, što je bio slučaj u konkretnom primeru. Stambeno naselje ugroženo bukom i livnica se nalaze na brdovitom terenu.

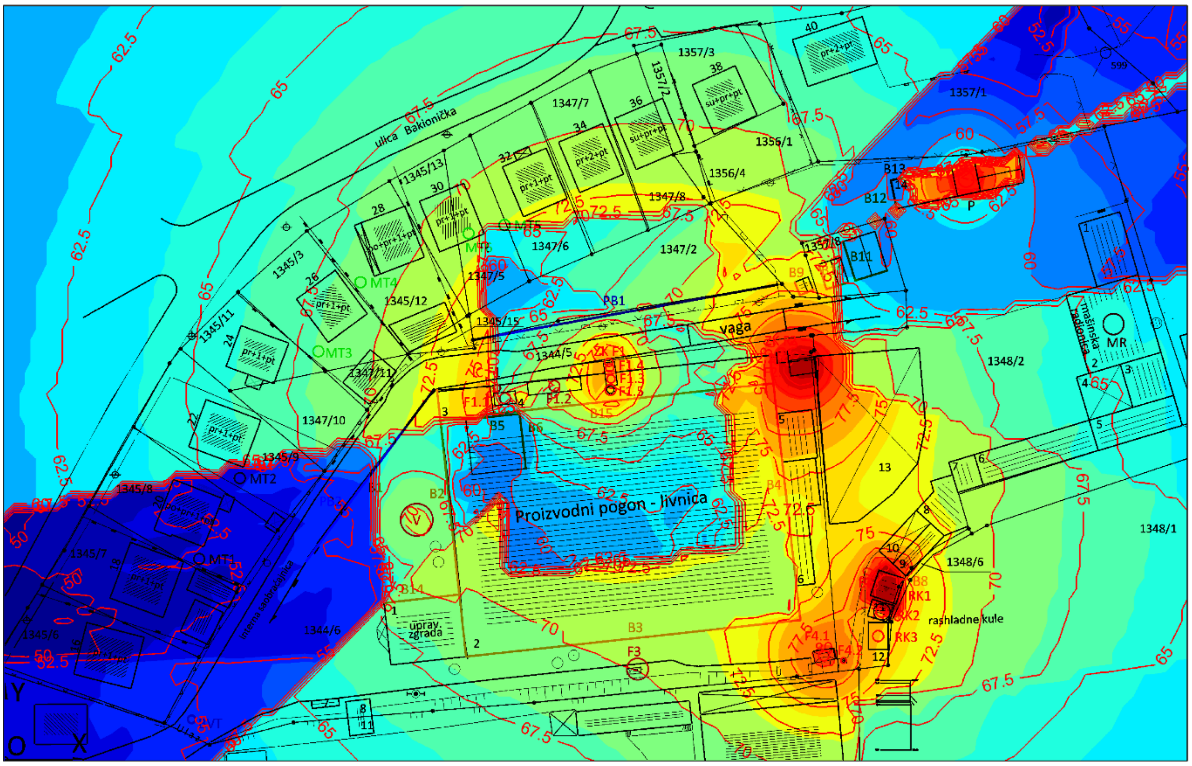
Zvučni izvori livnice nalaze se u visinskom rasponu od 17 m, a referentna merna tačka (MT5) ima visinsku koordinatu 10.5 m u odnosu na relativni koordinantni početak xOy, slika 6. Problem kod prikaza polja buke u ovakvoj situaciji je u tome što je ono izračunato za neku konkretnu visinu, nekada čak i za jednu mernu tačku, tako da ostale vrednosti u polju buke nisu od značaja za analizu. U takvoj situaciji potrebno je nacrtati veliki broj mapa buke, što otežava analizu problema. Najbolje je odrediti najugroženiju mernu tačku u zoni uticaja buke i nju proglasiti za referentnu. Vrednosti nivoa buke date u tabeli 1. su izračunate za tačno utvrđene koordinate mernih tačaka, koje su odgovarale pozicijama mikrofona tokom merenja nivoa buke.

Prilikom tumačenja rezultata koji su dobijeni primenom modela za prognozu buke treba uzeti u obzir okolnosti koje nije lako uvrstiti u model. Na mernoj tački MT1 odstupanje izmerenih i predviđenih vrednosti nivoa buke iznosi 2.5 dB. Na toj mernoj tački postoji uticaj buke od susednog preduzeća, pa je merna nesigurnost veća. Na mernoj tački MT4 je registrovano najveće odstupanje izmerenih i prognoziranih nivoa buke. Razlog za to je, što se ispred ovog mernog mesta na pravcu prostiranja zvučnih talasa nalazi pomoćni objekat za koji nisu postojali potrebni podaci da bi se on u modelu tretirao kao barijera.

Na referentnoj mernoj tački MT5, veoma je dobro poklapanje izmerenih i predviđenih vrednosti nivoa buke. Uzimajući u obzir sve uticajne faktore može se oceniti da je model za prognozu buke validan.

4.3. Izrada varijantnih rešenja i izbor konačne zvučne zaštite

Potrebno smanjenja nivoa buke zvučnih izvora određeno je na osnovu validnog modela prognoze buke koji je utvrđen u okviru tačke 4.2. Analizom dominantnih zvučnih izvora određeno je potrebno smanjenje nivoa buke četiri zvučna izvora sa maksimalnim nivoom buke.



Slika 6. Mapa buke pri maksimalnom random režimu svih zvučnih izvora u livnici

Potrebno smanjenje nivoa buke ΔL na dominantnim zvučnim izvorima, prikazano je u tabeli 2. Prilikom utvrđivanja nivoa redukcije buke vodilo se računa da potrebna smanjenja budu realno ostvariva

Tabela 2. Zvučni izvori koje je potrebno zaštititi

R. br.	Izvor	ΔL [dB]
1.	Dimnjak F1	10
2.	Motor i ventilator F1	6
3.	Dimnjak F2	10
4.	Motor i ventilator F2	7

Razmotrena je mogućnost izgradnje dve barijere na putu prenošenja zvuka, na mestima gde je to tehnički ostvarivo.

Tabela 3. Predložene barijere

Oznaka	Visina barijere [m]	Dužina barijere [m]
PB1	6	57,5
PB2	3	40

Na slici 3 predložene barijere su označene sa PB1 i PB2. Dimenzije predloženih barijera su date u tabeli 3. U zavisnosti od izbora, efikasnost zaštite zvučnom barijerom je reda (5 ÷ 15) dB.

Urađen je proračun sa dodatim predloženim barijerama i dobijene vrednosti su pokazale da predložene barijere imaju minimalan uticaj na nivo buke na referentnoj mernoj tački. Visina barijere PB1 bi trebala da bude veća od 10 m da bi ona imala uticaja na smanjenje nivoa buke. Takva vrednost visine barijere je iz tehničkih razloga neprihvatljiva. Kao konačno rešenje zaštite od buke dominantnih zvučnih izvora odabrane su metode višeslojnog oklapanja i izrade apsorpcionih prigušivača.

Centrifugalni ventilatori i njihovi pogonski motori kod oba filtera su okloljeni sa dvoslojnim oklopom na međusobnoj udaljenosti od 90 mm. Oklop je izrađen od apsorpcionih panela debljine 80 mm. Dimnjak filtera F2 je u potpunosti zamenjen sa apsorpcionim prigušivačem. Dimnjak filtera F1 je delimično zamenjen, tako što su ubačeni apsorpcioni segmenti i segmenti sa razdelnicima prigušenja. Na taj način dimnjak filtera F1 je realizovan kao kombinovani apsorpcioni prigušivač. Realizacijom mera zaštite od buke na navedenim zvučnim izvorima, očekuje se smanjenje nivoa buke na referentnoj tački (MT5) na vrednost od 54 dBA.

a) b)

Slika 7. Izvedeno rešenje dimnjaka i oklopa ventilatora i elektromotora filtera F1: a) 3D model segmenata dimnjaka filtera F1, b) Dimnjak i zaštitna kućica ventilatora i motora filtera F1

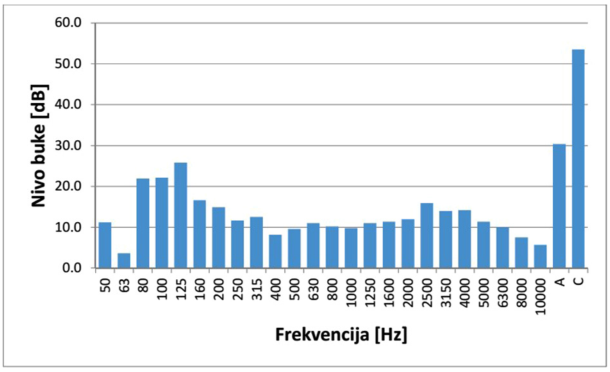
a) b)

Slika 8. Izvedeno rešenje dimnjaka i oklopa ventilatora i elektromotora filtera F2: a) 3D model dimnjaka filtera F2, b) Dimnjak i zaštitna kućica ventilatora i motora filtera F2

4.4. Efekti realizovane zaštite od buke

Nakon izvedene zvučne zaštite, izvršeno je merenje nivoa buke na istom mestu, u istoj prostoriji (MT6), kao što je učinjeno prilikom analize početnog stanja buke, slika 5.b. Uslovi merenja su bili potpuno identični, jer u međuvremenu na stambenoj jedinici u kojoj je vršeno merenje nisu preduzimane nikakve aktivnosti zvučne zaštite zidova ili zamene prozora. Pri maksimalnom radu svih zvučnih izvora u livnici izmeren je ekvivalentni nivo buke od 30 dB. Merama zaštite od buke ostvareno je sniženje nivoa buke u zatvorenom boravišnom prostoru za 14.5 dB(A). Ako ovo smanjenje izrazimo kroz odnos zvučnih pritisaka pre i posle zaštite, on iznosi 5.309 ili izraženo procentualno 530.9%.

Aerodinamička buka čiji je nivo na izlazu iz dimnjaka filtera iznosio 100 dB, imala je istaknuti ton na 250 Hz, slika 4.b. Rezultat završnog merenja, slika 9, je pokazao da je ova buka u potpunosti sanirana bez obzira na blizinu zvučnog izvora i njegovu visinu.



Slika 9. Frekvencijski spektar buke na mernoj tački MT6 nakon realizovanih mera zvučne zaštite (L_{Aeq} = 30.4 dB)

Uočljivo je da su nivoi buke na niskim frekvencijama od 80 Hz, 100 Hz, i 125 Hz i dalje ostale glavne komponente ukupne buke na mernom mestu. Nakon realizovane zvučne zaštite njihov nivo je za oko 15 dB niži, što je rezultiralo ukupnim smanjenjem nivoa buke za 14.5 dB.

5. ZAKLJUČAK

Veliko prekoračenje nivoa buke koje potiče od industrijskih izvora može se uspešno smanjiti na dozvoljeni nivo primenom metodologije koja je na primeru sistema za otprašivanje livnice prikazana u ovom radu. Metodologija sadrži analizu postojećeg stanja, formiranje modela za prognozu buke, izbor varijantnih rešenja uzimajući u obzir karakter buke i mogućnost njene promene, uz izbor parametara koji će omogućiti željeno smanjenje nivoa buke.

Izborom zvučne zaštite centrifugalnog ventilatora, elektromotora i dimnjaka filterskih postrojenja pokazano je da se može uticati na sve mehanizme generisanja zvučne energije: mehaničke, aerodinamičke i magnetne. Posebno treba istaći efekat smanjenja aerodinamičke buke koji je rešen primenom apsorpcionih prigušivača zvuka i promenom pravca zračenja zvučne energije, zaokretanjem završnih segmenata dimnjaka. Ostvareni efekti zaštite iskazani kroz frekvencijsku anallizu pokazuju da niskofrekvencijske komponente buke i dalje imaju najveći uticaj na nivo buke. Rezultati merenja su pokazali da su preduzete mere zvučne zaštite bile potpuno efektivne i dale su planirano smanjenje buke.

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Development of Methodology for the Industrial Noise Control in the Case of the Dedusting System of a Foundry

Branko Radičević[1], Mišo Bjelić[*1], Mile Savković[1], Nebojša Zdravković[1], Aleksandra Petrović[1]
[1] Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia

The article presents the methodology for industrial noise control in the case of the dedusting system of a foundry. The developed methodology starts from the fact that noise protection is possible at the source of noise itself, on the paths of sound waves, and at the place of reception. The model for noise prediction is the basis of the methodology for solving specific examples, which consists of two parts, the source model and the noise propagation model. The result of the model is a noise field, based on noise map creation time.

The activities in the procedure of noise protection are defined on a concrete example, and their interdependence is determined. Designing a noise protection system involves taking into account several functional, technological, and other limitations. Based on the required noise reduction of 15 dB in the nearest residential unit, variant noise protection solutions have been formed. The selection of the final noise protection solution was based on the techno-economic analysis.

Keywords: industrial noise, noise prediction model, dedusting system, sound absorption

1. INTRODUCTION

Modern equipment and modern casting technology enable the production of castings that have a wide range of applications. Most casting technological operations are characterized by high air dust, and that is the reason why is necessary to ensure the dedusting of the foundry. The dedusting of the foundry technological line and foundry furnaces can be made centrally or partially for each technological unit. A common foundry dedusting system consists of two independent units. The first unit consists of several technological facilities while the second unit consists of foundry furnaces. The foundry dedusting system presented in this paper is solved this way.

Each of these dedusting systems consists of one centrifugal fan which brings the dusty air into the bag filter by means of suction hoods and piping. Dedusting is carried out by a dry process using bag filters with pneumatic shaking. The dust is collected in bunkers and transferred to containers under the filter, which are periodically emptied. As a rule, such systems are large-sized and placed next to production halls so that they represent environmental noise generators.

Designing a noise protection system for dust collection systems is a very complex task. Therefore, it is necessary to develop a methodology for solving such problems. During the design process of noise protection, it is very important to be familiar with the functions of the system. Technological requirements, performed installations, the way of connecting the protection elements, and other influential factors are often obstacles during solving the noise protection problem.

This paper refers to the realized noise protection on a particular example of a foundry dedusting system. Based on the analysis of the current situation, the limit values of noise levels in the environment were exceeded. At the maximum mode of operation of the foundry, measurements in the nearest residential unit determined that the noise level was exceeded by 15 dB. Noise protection measures at the sources themselves have been designed and implemented. The possibility of building sound barriers on the path of sound wave transmission was considered, but given the terrain configuration, such a solution was found to be not effective. Application of the methodology presented in this paper, the noise level in the room where the exceedance was recorded was reduced to 30 dB. The legally established limit of environmental noise indicators indoors during the night period was achieved by protection measures.

2. PROBLEM ANALYSIS

The foundry dedusting facility is large-sized. The filter-based dedusting facility of the foundry technological lines is about 22 m long, taking into account the length of the pipeline, Fig.1a. The length of the bag filter body is 8 m while the height is 9 m. The height of the chimney is about 11 m. The speed of airflow in the pipelines is 23 m/s, based on the technical documentation. The power of the centrifugal fan is 125 kW, and the power of its electric drive motor is 132 kW. The filter plant is located next to the foundry, in the immediate vicinity of a residential area. The nearest residential unit is about 40 m away from the center of the filter facility. During its operation, the dedusting system generates a high noise level that exceeds the limit values of the environmental noise indicator. In further analyzes, this dedusting facility was marked as filter F1.

The second filter facility, Fig. 1.b, is used for the dedusting of foundry furnaces. It is smaller in size than the F1 filter and also is located at a greater distance from the residential area than the F1 filter. The speed of airflow in the pipelines is 20 m/s. The power of the centrifugal fan is 55 kW. The power of its electric drive motor is 75 kW. In further analyzes, the mentioned filter facility was marked as filter F2.

Besides the filter facilities, the cooling towers also belong to the category of dominant sound sources in relation to the noise level of sound sources. In relation to the residential area, the cooling towers are completely shielded by the high production facility of the foundry, which practically represents a sound barrier for the propagation

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* Corresponding author: Dositejeva 19, 36000 Kraljevo, bjelic.m@mfkv.kg.ac.rs

of noise from these sound sources. The noise from the sandblasting facility and the noise from the forklift in front of the foundry also has an impact on the noise levels in the residential area that is endangered by noise. A small street on the other side of a residential area has a negligible impact on the noise level at the measurement points which are selected for the assessment noise level generated by the foundry.

a)

b)

Figure 1. Most influential noise sources at the foundry: a) Filter F1, b) Filter F2

3. DEVELOPMENT OF METHODOLOGY FOR THE INDUSTRIAL NOISE CONTROL

Basic mechanisms of sound energy generation in the case of industrial sources can be mechanical, aerodynamic, and magnetic [10-12]. Bearing in mind these mechanisms, as well as possible principles of noise control at the sound source itself, at the path of sound waves, and at the receiver, it is possible to develop a large number of variant solutions of industrial noise control. Therefore, it is necessary to develop a methodology that will serve as a guideline for the implementation of knowledge in this area.

Implementation of the industrial noise control systems can be carried out following the methodology that consists of the following stages:

- Analysis of the current situation
- Formation of a noise forecasting model
- Selection of variant solutions to change the character of the noise
- Selection of parameters and some expected effects during the design of sound protection elements
- Production and installation of the noise protection elements
- Noise level measurement and verification of noise protection system

3.1. Analysis of the current situation

The analysis of the current situation begins with the investigation of environmental noise caused by industrial noise. In the case of an impact of other sound sources at the receiver place, such as traffic or some other source, it is necessary to determine the specific impact of industrial noise. The environmental noise level may exceed the limit values of noise indicators defined by law. Noise levels above the limits disturb people's rest, sleep, and work activities.

The analysis begins with the introduction to the functions and technological parameters of machines, equipment, devices, and facilities that are dominant noise sources. Control at the noise source belongs to the category of primary measures. Their implementation often eliminates the need for the application of other measures, on the path of sound wave transmission or at the place of the receiver. During the initial analysis of sound sources, it is necessary to identify all noise sources and to determine the main mechanisms of sound energy generation. The sound intensity method is the most efficient for locating dominant sound sources because its application can exclude the noise from other sources. Background noise is the most common disturbance factor when it comes to the application of other methods.

During the measurement of industrial noise, there are usually many sound sources with different principles of sound generation. In such a situation, the sound pressure measurement method can also be used for the identification of sound sources. The most important thing when applying this method is to determine the distance of the microphone from the sound source. The length of this distance depends on the principle of energy transmission from the source to the elastic medium. The mechanisms of sound wave formation can be the vibration of the solid surfaces, forced pulsation of air current, turbulence in fluids, and fast thermal actions. Previous experiences [2-9] have shown that the microphone is best to be placed immediately next to the sound source or at a distance not exceeding 0.5 m from it, to avoid the influence of other sound sources. It should be noted that this is a measurement of sound pressure in a close field that depends on the shape of the source. Due to the mentioned influences, it is necessary to correct the measured value of the sound pressure in the near field. The reduction of sound pressure from 3 dB to 6 dB depending on the mechanism of sound generation has been experimentally determined.

3.2. Formation of noise forecasting model

Noise forecasting models are usually realized as two-part. The first part presents the noise source model while the second part presents the noise propagation model. Such models can often replace experimental measurements, which sometimes cannot be carried out due to limiting factors. Calculation of noise levels in this way is especially important for the following cases: high background noise, development of planning documentation, development of alternative systems for noise protection, and development of contour maps. The application of such models provides detailed information about a huge number of sound sources and their individual or collective impact on the noise level at the receiver's place. This methodology allows the assessment of different hypothetical situations. Unlike real measurements, this methodology allows the elimination of the background noise as well as the influence of meteorological parameters. The disadvantages of this methodology are a large amount of necessary information considering terrain topography needed as well as geometry and dimensions of the objects that represent sound barriers. It is also necessary to know all dimensions of sound sources and the specific noise levels they generate. The height at which sound's acoustic center is located is especially important if that sound source is modeled as a point source. The results accuracy largely depends on the experience and skills of the person who is using the model.

Numerous national and international standards define different types of algorithms for noise forecasting. The algorithms are empirical and based on noise propagation dependencies. Many of these models are simple to use when one or a small number of sources are involved. The need to determine the noise level at a large number of points, and to observe a large number of sound sources at the same time, led to the use of computers. Computers enable faster calculation, analysis, and presentation of results in various formats. The most common way to represent the output results is to display the noise level in the grid nodes of the analyzed space. Based on the noise level at the grid nodes, a contour map that represents a visualization of the noise field is formed. Algorithms are usually oriented towards a certain type of source, which limits the possibility of their application. The exception is the algorithm defined by standard ISO 9613, which can be applied to any source for which sound power level data is known.

The main problem during the calculation of noise maps is the noise propagation model. Approximate formulas used in engineering models are derived under certain constraints, so their application requires careful use of input data. Local noise map calculation software [1] allows the calculation of the noise field generated by many point sources. Noise level at the receiver's place can be analyzed using the calculation results to check the influence of existing and desired line barriers. The noise field is represented by the noise levels in the nodes of the three-dimensional grid. The grid is formed with the desired grid step along three mutually perpendicular coordinate axes. The simplest case is terrain that is flat and horizontal, ie, there is no height difference between position of the sound sources and the receiver. Setting-up the height defines the position of an individual node point and thus the position of the plane in which the noise field is located, which is parallel to the substrate. If the terrain is bumpy, it is necessary to have information about the isohypses of the terrain. In addition to the values of the noise level at the grid nodes, it is possible to calculate the noise level at selected characteristic points in space, the so-called control points.

The calculation of the noise field is based on the ISO 9613 standard [13], according to the modifications adopted in domestic practice [1]. The calculation procedure assumes that the noise sources do not have a pronounced directivity and that all barriers are much wider than the wavelength of sound, in which case the diffraction can be neglected. Under the above assumptions, the noise level at the receiving point (L) can be calculated according to the expression (1):

$$L = L_w + C \tag{1}$$

where: Lw - sound power of the source, C - correction of sound level which can be expressed as (2):

$$C = C_{DA} + C_G + C_B \tag{2}$$

where: C_{DA} – correction due to wavefront propagation and absorption in the air, C_G – correction due to terrain absorption, C_B – correction due to barrier.

The values of the specified corrections are calculated according to the expressions (3-5):

$$C_{DA} = 11 - 20\log\left(s_\perp\right) - s_\perp/200 \ \left[dB\right] \tag{3}$$

where: $s_\perp$ - the shortest normal distance between the noise source and the receiving point.

$$C_G = \frac{h_m}{d}\left(34 + \frac{600}{d}\right) - 4.8 \ \left[dB\right] \tag{4}$$

where: h_m - the average height of the line connecting the noise source and the receiving point, d - length of that line.

The correction due to barrier is calculated according to the expression:

$$C_B = -7\log\left(5 + \frac{70 + 0.25 s_\perp}{1 + 0.2 s_\perp}\right) z_\perp K_{w\perp}^2 \ \left[dB\right] \tag{5}$$

where: $z_\perp$ - the difference between the paths of the diffracted and direct waves, expressed by the formula (6):

$$z_\perp = A_\perp + B_\perp + C_\perp - s_\perp \tag{6}$$

gde su: $A_\perp$ - the distance from the source to the upper edge of the barrier, $B_\perp$ - the distance from the receiver to the upper edge of the barrier, $B_\perp$ - the sum of the fragmented lengths of the edges in barriers with several fragmented edges.

Meteorological correction, $K_{w\perp}$, in expression (5) is determined according to the formula (7):

$$K_{w\perp} = \exp\left(-\frac{1}{200}\sqrt{\frac{A_\perp B_\perp s_\perp}{2 z_\perp}}\right) \ \left[dB\right] \tag{7}$$

This calculation procedure is primarily suitable when the noise level, which originates, from a large number of point sources, needs to be determined at the receiver's location. Therefore, it can be assumed that such sources form a complex non-periodic sound. The spectral components of a complex sound have different, equally probable phase positions at the receiver location, so that the total sound level at the receiver location can be calculated according to the expression: (8):

$$L_{Aeq,R} = 10\log\sum_{i=1}^{N} 10^{0.1 L_{Aeq,i}} \tag{8}$$

gde su : LAeq,i - noise level of the i-th source obtained applying the A-weight curve, N - the total number of sound sources.

Excess of the noise level at the receiver location can be classified as follows: smaller (up to 2 dB), medium (2÷5 dB), large (6÷10 dB) and very large (> 10 dB).

3.3. Selection of variant solutions in order to change the character of noise

During the design and manufacturing phase of technological systems that are potential sources of noise, different methods can be used to ensure quieter operation. This issue is defined by international standards, directives, and other legal acts, that provide guidelines for noise control on certain types of sound sources. Particularly strict requirements regarding noise emissions are there in case of equipment that works outdoors and can endanger the environment. Our legislation covers this area with the Rulebook on noise emitted by equipment used outdoors ("Official Gazette of RS", No. 1/2013). In addition to design and manufacturing, equipment maintenance can significantly affect the noise level that equipment generates.

Several basic principles of noise reduction should be adhered to in the case of equipment design, reconstruction, and maintenance. The atmosphere is a good high-pass filter. Due to that, the frequency content of the noise should be moved to higher frequencies. This can be seen in the example of a fan, where a changed number of impeller blades can change the frequency content of the noise and significantly reduce the zone of its harmful influence. Sudden changes in physical quantities that are characteristic of a movement or process, such as forces, pressure, and velocities, are used to generate noise at higher frequencies. The rate of change of force or pressure levels determines the frequency content so that a longer repetition interval creates low-frequency noise and vice versa. The higher elasticity of contact surfaces increases the duration of contacts which generates noise with a lower frequency content. The reduction of a large plate's surface area that is excited by vibrations significantly reduces the level of generated noise. A higher number of long and narrow moving elements generate a lower noise level, compared to one element of the same total area. Adding layers with a high vibration damping coefficient to metal surfaces can reduce the level of generated sound energy. The choice of plate joints with free ends prevents the occurrence of low-frequency noise. If a source of noise vibrates and is attached to the elements of the building structure at the same time there will be a generation of a structural sound. This problem can be solved by isolation of vibration using elastic substrates or springs or by building foundations for machines.

When it is not possible to perform sound protection of the source itself, control measures are applied on the paths of sound wave transmission. Control of airborne noise in the path of sound waves can be achieved by shielding the source, placing barriers or tunnels between the source and the receiver. The application of absorption chambers reduces the impact of reflected waves, and thus the generation of total noise level in the environment. Source shielding is performed in several different ways. The sound source can be shielded with absorbent material, solid material, or multi-layer armor. Barriers are placed in the path of sound waves from the source to the receiver, and noise levels are reduced by preventing sound waves from propagating. For the barrier to be fully effective, direct visibility of the receiver from the source position must be prevented.

3.4. Selection of parameters and some expected effects in the design of noise protection elements

Machines and devices used in the industry belong to the stationary sources, whose noise level depends on the installed power. Machinery used in industrial plants consists of electric motors, internal combustion engines, pumps, fans, compressors, transformers, generators, conveyors, reducers, cooling towers, ventilation systems. The main mechanisms of noise generation can be divided into three groups: mechanical, aerodynamic, and magnetic. Mechanical mechanisms of noise generation, such as imbalance, inconsistency, deviation from shape and position, can be successfully solved by monitoring their condition and applying preventive maintenance methods. Improper maintenance can lead to an increase in noise levels of up to 20 dB (A) [10]. The machines generate high levels of medium and high-frequency noise. The frequency components of the noise are proportional to the speed of rotation of the machine elements. The functioning of electrical machines is characterized by the existence of electromagnetic and mechanical forces, resulting in vibrations of the elements and surfaces of these machines, which results in noise creation.

Aerodynamic noise occurs as a consequence of fluid movement and its discharge at the places of executive elements of the pneumatic installation. This noise can be high if the fluid in its path has a lot of incidental and local obstacles where turbulence occurs. As a result of those turbulences broadband noise occurs. Besides, there are tonal components that occur as a result of the intersection of the fluid flow using rotating elements. In the case of several rotating components in the machine system, each of them can generate its own set of tonal components. Aerodynamic noise occurs in pneumatic conveyors used to transport grain, cement, coal dust, fine coal, wood sawdust, ash, and other materials. Material that hits against the walls of the pipes, in places where the flow direction changes or at the points where other obstacles occur, creates air turbulence, which leads to an additional increase in noise levels. Pneumatic conveyors are generally of great length, placed in the open space, so they represent a significant source of environmental noise.

The principle of pneumatic transport was used in the foundry dedusting system presented in this paper. Particles of dust, sand, and technological vapors are extracted into the pipeline using suction hoods and transported to filter plants from where the purified air is released into the atmosphere through the chimney. Noise protection of such a system can be realized if all noise generation mechanisms and all noise control principles are taken into account.

Figure 2 shows three ways of sound sources shielding. It is important to point out the noise reduction effects of each of the listed solutions [10]. Source shielding using absorption material without discontinuation of the vibration propagation paths, can reduce noise about 3-5 dB, Fig. 2.a. The same armor, made of solid material, under the same conditions reduces the noise level in the range of 3-10 dB, Fig. 2.b. The most effective way of shielding is a multi-layer shielding, as shown in Fig. 2.c. If conditions allow, it is best to make one layer of absorbent material and the other of solid material. The reason for that lies in the fact that a barrier that has a larger mass better absorbs low frequencies of the sound wave, and the absorbent material better absorbs medium and high frequencies of noise. Shield, with several layers of dissimilar materials, Fig. 2.c, where the propagation of vibrations is reduced using elastic materials, can give a noise reduction effect of over 20 dB. The problem arises when necessary to make ventilation openings on the shield. The openings are usually made for the supply of fresh air for cooling purposes. A better way to solve this problem is ventilation ducts that are padded with absorption material from the inside.

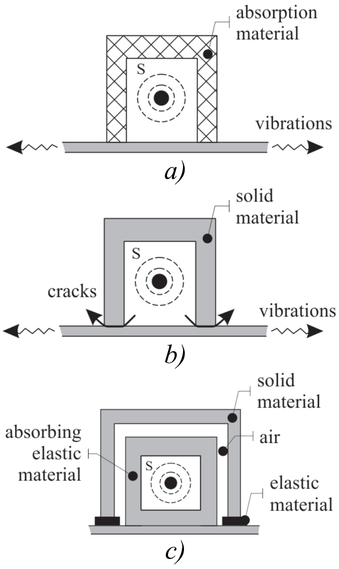


Figure 2. Types and expected effects of noise reduction in case of shielded sound sources [10]

4. RESULTS AND DISCUSSION OF IMPLEMENTED NOISE PROTECTION ON THE EXAMPLE OF FOUNDRY DEDUCTION SYSTEM

4.1. Analysis of the current situation

A combined cadastral-topographic plan was used as a basis for the formation of a digital model of the terrain and also a model of the objects on the terrain. This plan contains the representation of the terrain's position and height as well as the positions of all facilities and supporting infrastructure. The plan also contains official boundaries of the cadastral parcels of the area where the foundry is located and the boundaries of the residential area that is endangered by noise. Besides, the position of all underground and aboveground infrastructure lines has been entered. Based on the technical documentation and on-site inspection, a wider set of influential sound sources that generate environmental noise has been defined. During the problem analysis (section 2), dominant sound sources were defined and listed, based on the sound pressure level that is determined in the manner shown in section 3.1.

Figure 3 shows the most influential foundry's noise sources. On the north side of the production facility, there is a group of noise sources that belong to the filter subsystems F1 and F2, which are closest to the residential area. The production facility is surrounded by many noise sources: on the south side, there is the filter (marked as F3), on the southeast, there is the cooling tower (marked as RK), on the east, there is the machine shop (marked as MR), on the northeast, there is sandblast (marked as P) and on the west side there is forklift (marked as V). The same figure shows the existing barriers (marked as B). They represent the walls of existing buildings, which are located on the way of sound waves propagation towards the residential area. In addition to the existing ones, the position of the planned barriers (marked as PB) is presented. The impact of those barriers was analyzed as a part of variant solutions for noise protection. In the previous period, the foundry implemented noise protection measures for both centrifugal fans and their electric motors (Fig. 1). The protection implied partial shielding using absorption panels. This solution did not give satisfactory sound protection effects towards the residential area. The possibility of integrating partial protection into a multilayer armor system, which was proposed, and later implemented as

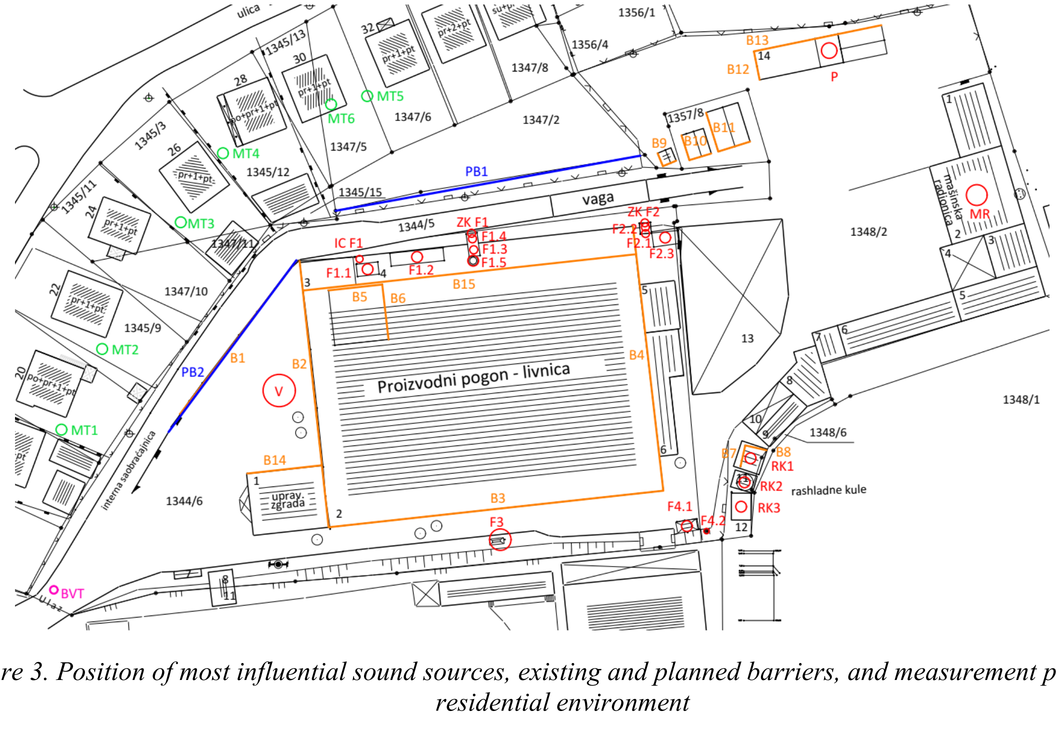


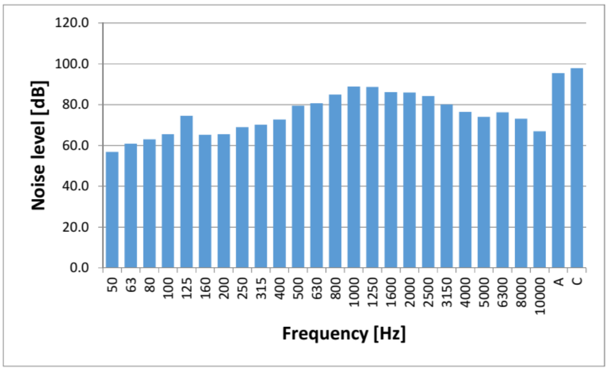
Figure 3. Position of most influential sound sources, existing and planned barriers, and measurement points in the residential environment

sound protection, was also considered.

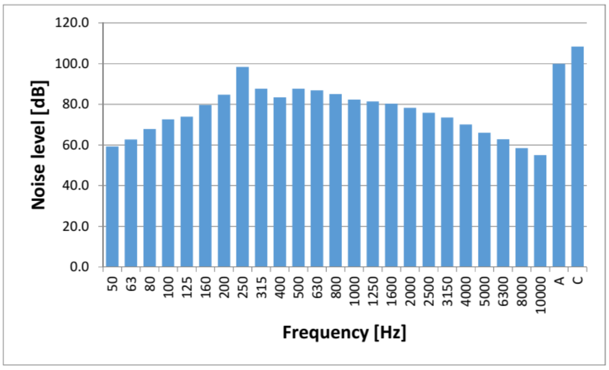
All identified sound sources were measured and analyzed to determine the dominant sound sources in the foundry. The set of most influential sources consisted of sources whose noise level is lower for less than 10 dB, than the source with the maximum sound pressure level.

The measurement points in the residential area were marked as MT. Measurements showed that the measurement point marked as MT5 has the highest level of external noise. The equivalent noise level at this measurement point was 61.4 dB (A). In further analyses, this measurement point was marked as a reference point for noise assessment in the entire residential area.

The nearest housing unit, located next to the reference point was selected for indoor measurement. The measurement was performed in the living room on the first floor because it was closest to the noise sources. This measurement point was marked as MT6. With all the windows and doors closed, an equivalent noise level of 44.9 dB (A) was measured at the measurement point, which was located in the middle of the room. The room in which the measurement was performed has a relatively old wooden window with double wings.



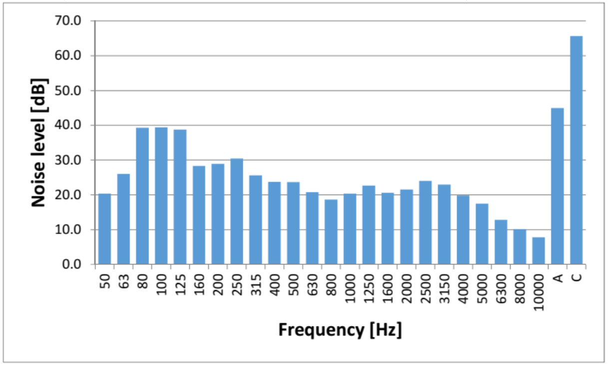
a)



b)

Figure 4. The noise frequency spectrum in case of the source with the highest noise level: a) The noise frequency spectrum of F1 filter fan drive motor (L_{Aeq} = 95.4 dB), b) The noise frequency spectrum of aerodynamic noise at the outlet of the chimney filter F1 (L_{Aeq} = 100.0 dB)

According to the standard SRPS U.J6.201 [15], the mentioned window can be classified as class IV, in relation to the insulating power of 20÷24 dB. The main goal of the sound protection system was to lower the noise level at the measurement point MT6 to the level of 30 dB (A), which is the limit value of environmental indoor noise indicators during the night, according to the current Regulation ("Official Gazette of RS" No. 75/2010).



a)

b)

Figure 5. The noise frequency spectrum for the most endangered room on the first floor of the house (MT6): a) The noise frequency spectrum at measurement point MT6, (L_{Aeq} = 44.9 dB), b) Measurement point MT6 (40 m from the chimney filter F1)

4.2. Noise forecasting in an endangered residential area

The noise forecast in the residential zone endangered by noise was performed using the Bel-Cho software, which was developed at the Faculty of Mechanical and Civil Engineering in Kraljevo of the University of Kragujevac. The software is based on the calculation steps, defined in section 3.2 of this paper. A detailed description of the software can be found in [1].

Table 1. Validation of the noise map at control points

Measurment point	Model (noise map) [dBA]	Measured noise level [dBA]	Difference [dBA]
MT1	57.2	59.7	2.5
MT2	59.8	60.6	0.8
MT3	59.8	60.6	0.8
MT4	64.0	60.5	3.5
MT5	61.7	61.4	0.3

The application of Bel-Cho software is difficult when the terrain is not flat as in this case. The residential area endangered by noise is located on hilly terrain, as well as the foundry. The sound sources of the foundry are located in the height range of 17 m. The referent measurement point (marked as MT5) has a height coordinate of 10.5 m concerning the origin of the relative coordinate system xOy (Fig. 6). Visualization of the noise field in this situation is problematic because that noise field is calculated for a specific height, sometimes even for one measurement point, so that other values in the noise field are not relevant for analysis. In such a case, it is necessary to draw many noise maps, which makes analysis of the problem difficult. The best solution is to find the most endangered measurement point and to declare it as a reference. The noise levels, Table 1, were calculated for specific coordinates of the measurement points, that corresponded to the position of the microphone during the measurement. During the interpretation of the results obtained by the noise forecasting model, circumstances that are not easy to include in the model should be taken into account. At the measurement point MT1, the deviation between measured and predicted noise level was 2.5 dB. Higher uncertainty at that measurement point is a consequence of the noise from the company located nearby. The largest deviation of measured and forecasted noise levels was registered at the measurement point marked as MT4. The reason for this deviation, is an auxiliary object which is located in the front of this measurement point, in the direction of sound wave propagation, and for which there was no necessary data to treat it as a barrier in the model. At the reference point, marked as MT5, the agreement between measured and predicted values of the noise level was very good. Taking into account all the influential factors, it can be concluded that the noise forecasting model is valid.

4.3. Development of variant solutions and selection of final solution

The required level of noise reduction was determined based on a validated noise forecasting model. The analysis of the most influential sound sources was used as a basis for the determination of the necessary noise reduction in the case of the four sound sources with the maximum noise level.

The required level of noise reduction, ΔL, in the case of the most influential sound sources, is shown in Table 2. The required levels of noise reduction needed to be realistically achievable. The possibility of construction of two barriers on the path of sound transmission, in places where it is technically possible, was considered. The proposed barriers are marked as PB1 and PB2, Fig. 3. The dimensions of the proposed barriers are given in Table 3. Depending on the choice, the sound barrier protection efficiency was in the range from 5 to 15 dB.

Table 2. Sound sources that need to be protected

No.	**Sound source**	**ΔL [dB]**
1.	Chimney F1	10
2.	Motor and fan F1	6
3.	Chimney F2	10
4.	Motor and fan F2	7

Table 3. Proposed barriers

Mark	**Barrier height [m]**	**Barrier lenght [m]**
PB1	6	57,5
PB2	3	40

The values of noise levels obtained by additional calculations with the participation of proposed barriers showed that the proposed barriers have a minimal impact on the noise level at the reference measurement point. The height of the barrier marked as PB1 should be greater than 10 m to reduce noise levels. Such a value of the barrier height is unacceptable for technical reasons.

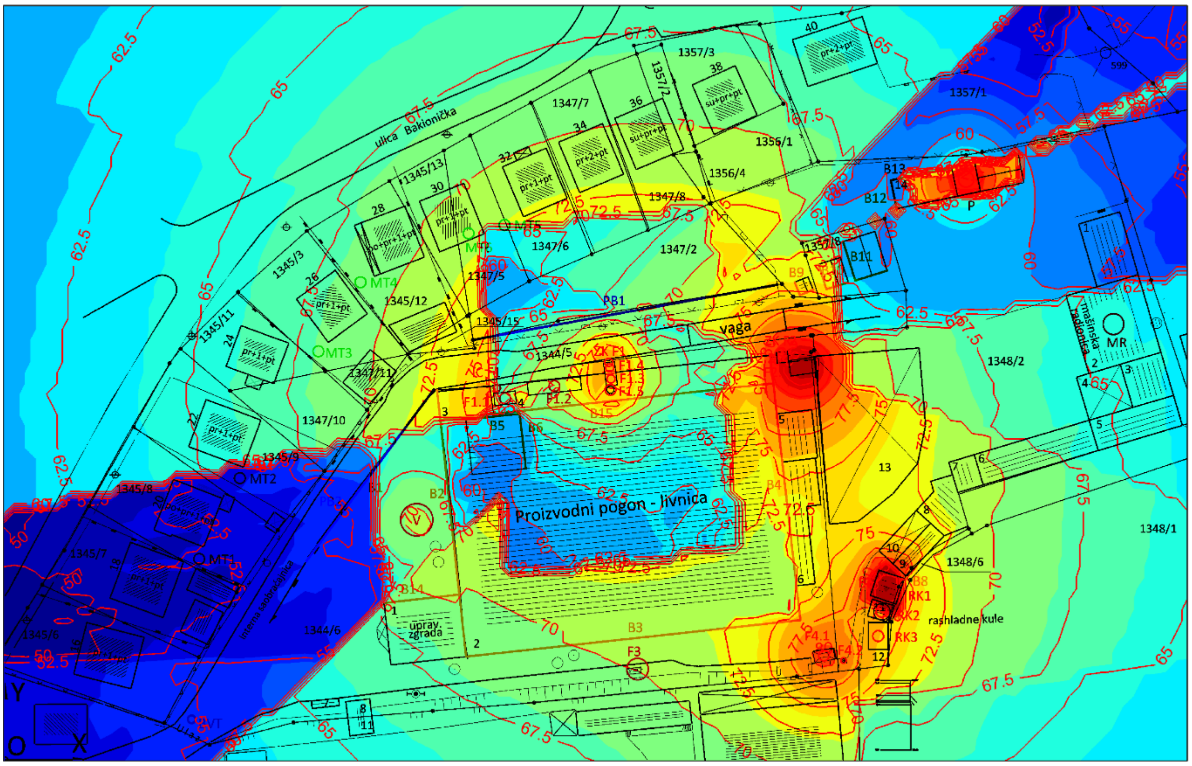


Figure 6. Noise map in the case of maximum operating mode of all sound sources in the foundry

The multilayer shielding method, combined with the fabrication of absorption attenuators, was selected as the final noise protection solution. The centrifugal fans and their drive motors in both filters were shielded with a two-layer shield, at a distance of 90 mm from each other. The shield was made of 80 mm thick absorption panels. The chimney filter F2 has been completely replaced with an absorption silencer. The chimney of the F1 filter has been partially replaced by insertions made of absorption segments and segments with damping dividers. That way, the chimney of the F1 filter was realized as a combined absorption silencer. After the implementation of noise protection, the expected value of noise level at the reference point (MT5) was 54 dBA.

a) b)

Figure 7. Izvedeno rešenje dimnjaka i oklopa ventilatora i elektromotora filtera F1: a) 3D model of chimney F1 filter segments, b) Chimney and protective housing of the F1 filter's fan and motor

a) b)

Figure 8. Izvedeno rešenje dimnjaka i oklopa ventilatora i elektromotora filtera F2: a) 3D model of chimney F2 filter segments, b) Chimney and protective housing of the F2 filter's fan and motor

4.4. The effects of implemented noise protection

After the realization of sound protection, the noise level was measured at the same place in the same room (MT6), as was measured during the analysis of the initial noise state (Fig. 5 b.). The conditions of the measurement were completely identical because, in the meantime, at the residential unit, there were no sound protection activities like wall isolation or windows replacement. During the measurement, an equivalent noise level of 30 dB was measured at the maximum operation level of all sound sources in the foundry. Noise protection measures reduced the noise level in the closed living space by 14.5 dB (A). If we express this decrease through the ratio of sound pressures before and after protection, it amounts to 5.309 or 530.9%.

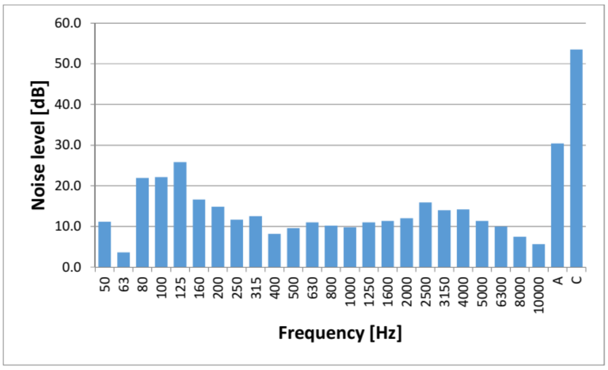


Figure 9. The noise frequency spectrum at measurement point MT6, after realized sound protection (L_{Aeq} = 30.4 dB)

The aerodynamic noise, which level was 100 dB at the outlet of the filter chimney, had a prominent tone at 250 Hz (Fig. 4.b.). The result of the final measurement (Fig. 9) showed that this noise was completely remedied regardless of the proximity of the sound source and its height. It can be noticed that the noise levels at low frequencies of 80 Hz, 100 Hz, and 125 Hz were still the main components of the total noise at the measurement point. After the realized protection, their level is about 15 dB lower, which resulted in an overall reduction of the noise level by 14.5 dB.

5. CONCLUSION

Huge excesses of noise levels that originate from industrial sources can be successfully reduced to the permitted level using the methodology presented in this paper based on the example of a foundry dedusting system. The methodology contains an analysis of the existing situation, the formation of a noise forecasting model, the selection of variant solutions considering the character of noise, and the possibility of its change, with the selection of parameters that will enable the desired level of noise reduction.

Proper choice of the sound protection solution, in case of the centrifugal fan, electric motor, and chimney of filter facilities, has shown that it is possible to make the influence on all mechanisms of sound energy generation: mechanical, aerodynamic, and magnetic. Special emphasis should be placed on the effect of aerodynamic noise reduction, which was achieved using absorption attenuators and by the change of the sound energy radiation direction rotating the final segments of the chimney. The achieved protection effects, expressed through frequency analysis, showed that low-frequency noise components still have the greatest impact on the noise level. The results of measurements showed that the applied sound protection measures were completely effective and gave the planned level of noise reduction.

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