© Strojniški vestnik 45(1999)7/8,287-293 © Journal of Mechanical Engineering 45(1999)7/8,287-293
ISSN 0039-2480 ISSN 0039-2480
UDK 648.23:534.83 UDC 648.23:534.83
Strokovni članek (1.04) Speciality paper (1.04)

Zmanjšanje hrupa pralnih strojev z uporabo dušilnih materialov

The Reduction of Washing Machine Noise by the Use of Muffling Materials

Nikola Holeček

V članku je najprej prikazan pregled modeliranja vibracij pralnikov Gorenje. Sledi prikaz eksperimentalne metode določanja zvočne moči in potek zniževanja hrupa pralnika z uporabo dušilnih materialov.

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(Ključne besede: stroji pralni, modeliranje vibracij, hrupnost strojev, materiali dušilni)

This paper begins with an overview of the modelling of the dynamical behaviour of Gorenje washing machines. Subsequently there is a presentation of the experimental method of defining sound intensity and the procedure for the reduction of washing machine noise by the use of muffling materials.

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(Keywords: washing machine, vibration modells, machine noise, muffling materials)

0 UVOD

Razvoj velikih gospodinjskih aparatov se v zadnjih letih vedno bolj usmerja k zmanjševanju hrupnosti strojev. Od leta 1996 je v veljavi priporočilo evropskega združenja 92/75/EWG, ki predpisuje razglasitev emisijske ravni hrupa pralnih strojev in informiranje porabnikov z ustrezno nalepko, ki vsebuje podatek o ravni zvočne moči pri pranju in ožemanju.

Svetovni trg terja mirnejše, tišje in varčnejše pralne stroje z večjo vrtilno frekvenco bobna pri ožemanju. Dinamične obremenitve se večajo s kvadratom vrtilne frekvence, kar se kaže v manjši mirnosti teka pralnika in v višji ravni hrupnosti. Sedanja priporočila za raven zvočne moči predpisujejo celotno raven manjšo od 65 dB pri ožemanju, ne glede na vrtilno frekvenco ožemanja.

Metode za merjenje zvočne moči so standardizirane (ISO 3745), prav tako je predpisan način delovanja naprave, ki jo merimo (IEC 704-2-4 za pralne stroje).

Poudariti je treba, da se mencanje in centrifuga glede problematike zmanjšanja hrupnosti povsem izključujeta. Medtem ko na

0 INTRODUCTION

In recent years one of the trends in the development of large household appliances is the reduction of noise. In 1996 the Directive of European Community 92/75/EWG came into force, according to which the noise levels of individual washing machines have to be declared, and customers have to be informed by means of an appropriate label containing information about the level of sound power during washing as well as during spinning.

The world market demands quieter and more economical washing machines with higher rotation speed of the drum during spinning. Dynamic loading is increased by the square of the rotation speed which can cause vibration of the washing machine and higher noise levels. The present recommendations for the level of sound power define the total level to be lower than 65 dB during spinning, regardless of the rotation speed of the machine.

The methods for measuring the sound power are standardised (ISO 3745), as well as the way in which the appliance is operated, which for washing machines is IEC 704-2-4.

It should be pointed out that tumbling and spinning are, as far as the problem of noise reduction is concerned, mutually exclusive. While the hrupnost pri mencanju vpliva predvsem elektromotor, vpliva pri centrifugi, zaradi problemov z neuravnoteženostjo perila, na hrupnost konstrukcija pralnega stroja in elastični deli, ki blažijo vibracije in udarce.

V prispevku je v nadaljevanju najprej na kratko prikazan potek modeliranja vibracij pralne skupine v domačem strokovnem okolju.

1 PREGLED MODELIRANJA VIBRACIJ

Modeliranje dinamičnega obnašanja pralnika ter predvsem njegove pralne skupine se je odvijalo v okviru Laboratorija za dinamiko strojev in konstrukcij Fakultete za strojništvo v Ljubljani.

Na začetku je bil postavljen osnovni ravninski model pralne skupine s tremi prostostnimi stopnjami. Pri preučevanju zagona smo uporabljali izmerjeni časovni potek vrtilne frekvence bobna pri ožemanju. V nadaljevanju smo preučevali ujetje sistema v resonančnem področju ter vpliv sile teže rotorja na dinamično obnašanje pralnika. Sledila je razširitev modela z vključitvijo gibanja okrova pralnika, kar je pomenilo upoštevanje sedem prostostnih stopenj. Izkazalo se je, da so prednosti tako razširjenega modela premajhne glede na obsežnost dela.

Nato je sledila poglobitev teoretičnega postopka modeliranja z uporabo modernih metod iz teorije nelinearnih dinamskih sistemov. Obravnavo dinamičnega obnašanja pralne skupine smo razširili na fazni prostor, tako na pravi fazni prostor na podlagi integracije gibalnih diferencialnih enačb kakor tudi na rekonstruirani na podlagi meritve ene same spremenljivke. Dobili smo dobro ujemanje pri oceni korelacijske dimenzije med modelom in preskusom.

electromotor influences the noise during tumbling, the design of the washing machine and the elastic parts, which reduce vibrations and strokes, due to problems with unbalanced laundry, influence the noise level during spinning.

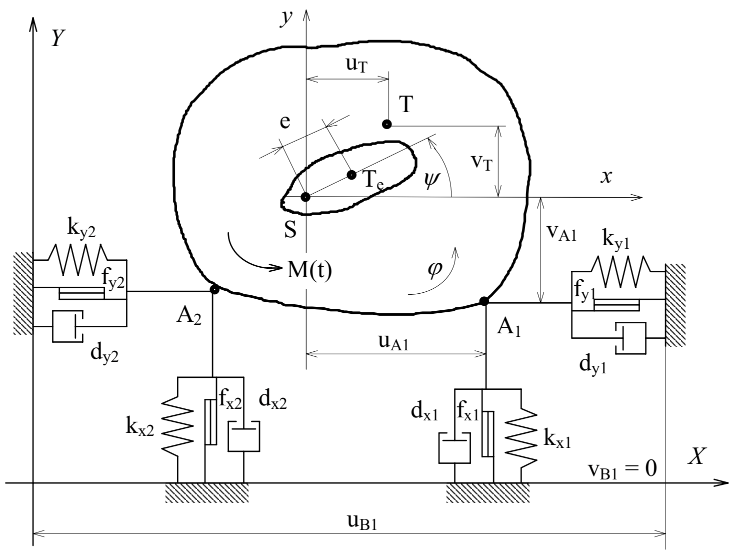
In this paper, first of all, a short overview describing the modelling of the dynamical behaviour of the washing machine in Slovenian institutions is given.

1 AN OVERVIEW OF MODELLING VIBRATIONS

The modelling of the vibrational behaviour of the washing machine was conducted in the Laboratory for Dynamics of Machines and Structures, Faculty of Mechanical Engineering in Ljubljana.

Initially, the basic planar model that consisted of three degrees of freedom was set up. Startup behaviour was studied by employing the measured drum angular velocity. The next step introduced the study of spin-up through resonance including the influence of the drum weight. The basic planar model was also extended into a system of two planar rigid bodies with seven degrees of freedom. However, the benefit from such an extension was not sufficient when compared to the increased level of complexity.

The next important step in theoretical modelling was orientated towards modern methods from the theory of non-linear dynamical systems. The description of the dynamical behaviour of the washing complex was expanded into the phase space of the system. The real phase space was based on the integration of the governing differential equations of motion while the reconstructed one was based on a single measured time history, employing the embedding theorem. In the estimation of the correlation dimension, good agreement between the model and the experiment was found.



Sl. 1. *Model pralne skupine*

Fig. 1. *Model of washing group*

V zadnjem času je bila izvedena tudi bispektralna analiza dinamičnih odzivov pralne skupine pri ožemanju. Vrednosti kvadratične bikoherence so dokazale kvadratično sklapljanje faz med posameznimi frekvenčnimi komponentami dinamike pralne skupine ter s tem povezano nelinearnostjo sistema.

Glavnina povzetega dela pri modeliranju dinamike pralnika je opisana v [1] do [3], sam model pa je prikazan na sliki 1.

Ne glede na obseg modeliranja vibracij ter na njihov nadzor pri realnem pralniku se vibracijam ne da izogniti. Zato pri praktičnem zmanjševanju hrupnosti pralnika uporabimo tudi dušenje strukturnega hrupa z dodajanjem izolacijskih materialov.

Just recently, the bispectral analysis of the vibrational responses of the washing complex at spinning was performed. The values of bicoherence squared showed some quadratic phase coupling between spectral components and thus confirmed the non-linearity of the system.

The major part of the described theoretical modelling is shown in [1] to [3]. The model itself is shown in Fig. 1.

Irrespective of the extent of vibrational modelling as well as their control on a real washing machine, the vibrations cannot be avoided. Consequently, the noise as a result of the remaining vibrations must be tackled also in a passive way. In the following, the use of insulating materials in order to reduce structure-born noise is described.

2 AKUSTIČNE MERITVE

Pri meritvah smo uporabljali metodo merjenja zvočne moči. Zvočna moč da informacijo o zvoku tako po smeri kakor po vrednosti:

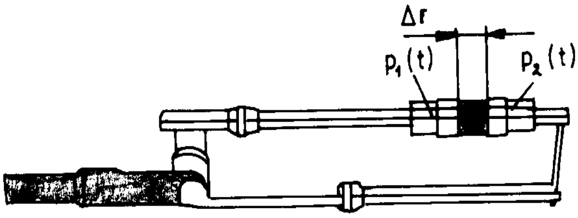
2 ACOUSTIC MEASUREMENTS

The method of measuring sound intensity was used. Sound intensity provides information about the sound direction as well as its value:

$$I = \frac{W}{A} = \frac{F}{A} \cdot v = p \cdot v \qquad (1).$$

V nasprotju z meritvami zvočnega tlaka (merimo ga neposredno z mikrofoni), zvočno moč določamo v dejanskem času z merjenjem zvočnega tlaka in hitrosti delcev. Odjemnik, ki hkrati meri zvočni tlak in hitrost delcev, je sonda za jakost. Sonda ima dva nasprotno si ležeča mikrofona za zvočni tlak. Mikrofona sta na razdalji Δr (sl. 2) [4].

Unlike noise pressure measurements (it is measured directly by microphones), noise intensity is determined in real time by measuring the sound pressure and the speed of the particles. The receiver, which simultaneously measures sound pressure and the speed of the particles, is the probe for intensity. The probe has two microphones for sound pressure which are placed opposite each other. The distance between the microphones is Δr (Fig.2) [4].



Sl. 2. *Sonda za merjenje zvočne jakosti*
Fig. 2. *Probe for measuring sound intensity*

2.1 Merjenje hitrosti delcev na podlagi razlike tlakov

Če je povprečni zvočni tlak $\bar{p} = \frac{p_1 + p_2}{2}$, je jakost vzdolž merilne sonde [5] do [7]:

2.1 Measuring the speed of particles on the basis of pressure difference

If the average sound pressure is $\bar{p} = \frac{p_1 + p_2}{2}$, the intensity along the measuring probe is [5] to [7]:

$$I_n = p \cdot v_n = \frac{p_1 + p_2}{2} \frac{1}{\rho} \int_0^t \frac{p_1 - p_2}{\Delta r} dt$$
$$I_n = \frac{p_1 + p_2}{2 \rho \Delta r} \int_0^t (p_1 - p_2) dt \qquad (2).$$

2.2 Sonda za merjenje zvočne jakosti

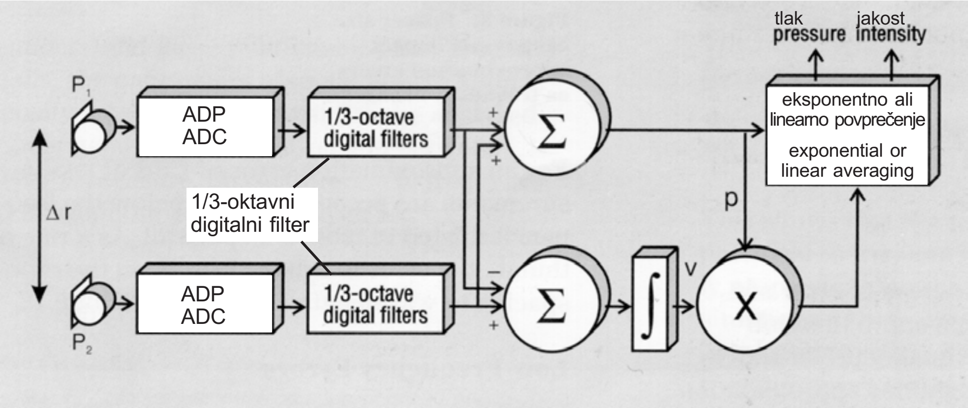
Sonda ima dva nasprotno si ležeča mikrofona, ki sta fazno prilagojena. Med mikrofonoma je vgrajen ustrezen vmesnik, glede na frekvenčno območje, ki ga merimo. Za področje 50 Hz do 6300 Hz se uporablja 0,5 palčni mikrofon, za višje frekvence so bolj primerni 0,25 palčni mikrofoni.

Iz merilne sonde vodimo signal na analizator zvočne jakosti. Pomembno vlogo za natančnost meritev ima fazna prilagojenost mikrofonov in ustrezni vmesnik [6].

2.2 Probe for measuring sound intensity

The probe has two microphones placed opposite each other and phase adjusted. There is an appropriate interface built between the microphones, according to the frequency range which is being measured. For the range from 50 Hz to 6300 Hz a 0.5 inch microphone is used, whereas 0.25 inch microphones are more suitable for higher frequencies.

The signal is fed from the measuring probe into the sound intensity analyser. Phase adjustment of the microphones and an appropriate interface play an important role in precise measurements [6].



Sl. 3. *Shema izračuna zvočne jakosti*
Fig. 3. *Scheme of calculation of sound intensity*

3 ZMANJŠANJE HRUPA

Hrupnost pralnega stroja je odvisna od: konstrukcije, elektromotorja, gumijastih delov, ki blažijo vibracije, ter od zvočne izolacije. Vsak od navedenih delov ima svoje lastnosti, ki prispevajo k zmanjšanju ali povečanju hrupnosti. Čeprav je zmanjševanje hrupa na poti njegovega širjenja tehnično najbolj učinkovito (uporaba dušilnih materialov ali materialov, ki dušijo prenašanje vibracij - kompozitna pločevina), smo svoja prizadevanja usmerjali tudi na zmanjševanje hrupa na izvoru, ker je to z energetskega in ekološkega vidika najbolj upravičeno.

Po deležu seveda k zmanjšanju hrupnosti največ prispeva izolacija. Zato smo ji tudi posvetili največ raziskav. Ker smo si zadali tudi cenovno omejitev, je bilo potrebno s čim manj izolacije in s čim cenejšo izolacijo doseči našo ciljno vrednost. Opravljena je bila množica meritev v polgluhi komori laboratorija za akustiko in vibracije. Z merjenjem zvočne moči po vseh petih sevalnih površinah smo določili mesta največjih sevanj in se je temu primerno oblikovala tudi izolacija. Kot izolacijske materiale smo preskušali:

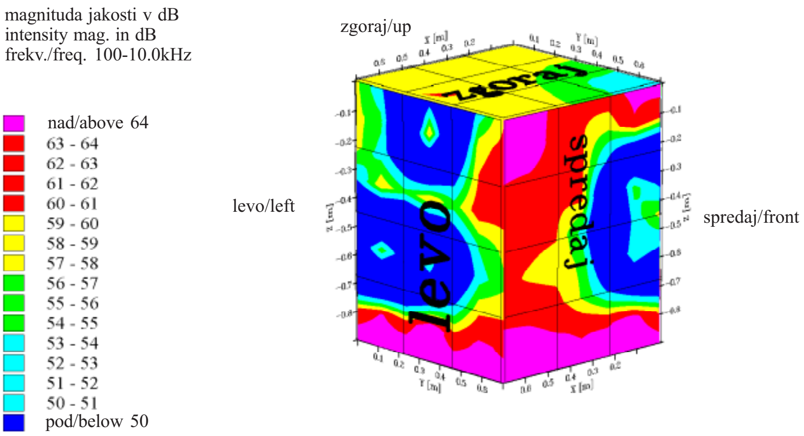
- kompozitno pločevino,
- poliuretansko peno (gladko in piramidno),
- cefrana odpadna tekstilna vlakna bombaža,
- težke mase.

3 NOISE REDUCTION

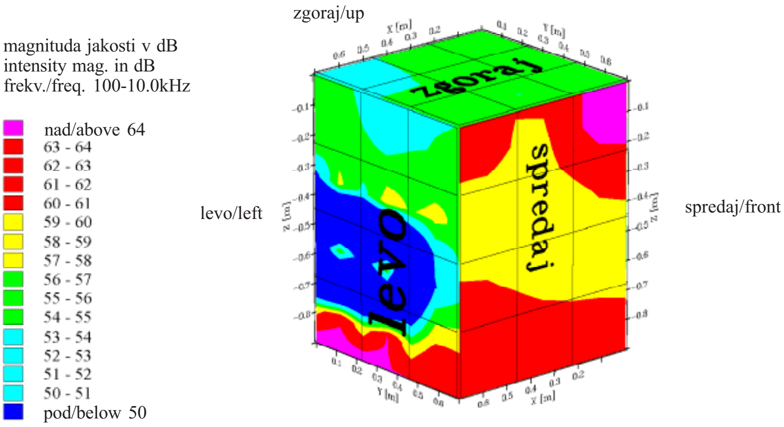
The noise of a washing machine depends on: the design of the washing machine, the electromotor, rubber parts for absorbing vibrations, and sound insulation of the washing machine itself. Each of the mentioned parts has its own characteristics which contribute to the increase or reduction in noise. Although noise reduction during its transfer is technically the most effective (use of muffling materials or materials which muffle transfer of vibrations - composite sheet metal), our efforts have been directed also to the reduction of noise at its origin, which is the most justified from the energy and ecology point of view.

Insulation is certainly the most important method for noise reduction and this is why most research has been dedicated to it. As we also took into account cost limitations it was necessary to reach our target value with the cheapest insulation possible. Numerous measurements were done in the half deaf chamber of the laboratory for acoustics and vibrations. By measuring sound intensity along all five radiation surfaces the places of the highest radiation were localised and insulation was created according to this. We have tested the following as potential insulation materials:

- composite sheet metal,
- polyurethane foam (smooth and pyramid),
- frayed waste textile cotton fibres,
- heavy masses.



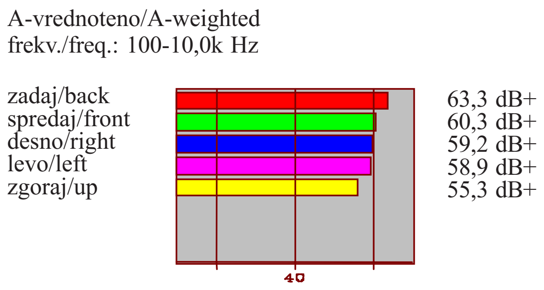
Sl. 4. *Ožemanje - delno izoliran stroj - zorni kot spredaj-levo*
Fig. 4. *Spinning - partly insulated machine - angle of sight front-left*



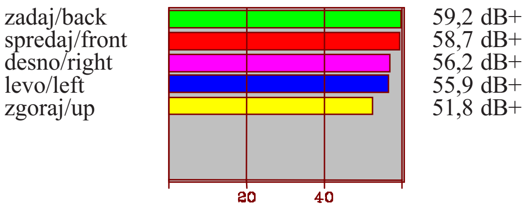
Sl. 5. *Ožemanje - v celoti izoliran stroj - zorni kot spredaj-levo*
Fig. 5. *Spinning - totally insulated machine - angle of sight front-left*

Primerjava med meritvijo delno in v celoti izoliranega stroja tako pri mencanju kakor ožemanju kaže, da nam je z izolacijo uspelo znižati hrup na vseh kritičnih mestih. Dodatna izolacija BORGERS (cefrana odpadna tekstilna vlakna bombaža) ima veliko večji učinek na zmanjšanje zvočne moči stroja pri mencanju - za 7,7 dB - kakor pri ožemanju - za 2,5 dB. Pri ožemanju je bistveni element dobro izolirana prednja stena. Posebno pozornost velja posvetiti tudi robovom na dnu stroja. Vse stranice na stroju so lahko znaten vir hrupa, zato je pomembno, da je izolirana celotna naprava. To velja tudi za zadnjo steno, katera sicer ni izpostavljena velikim vibracijam kakor sprednja ali bočne stene, vendar lahko kljub temu oddaja veliko zvočno moč. Pri meritvi zvočne moči delno izoliranega stroja je bila zadnja stena najmanj izolirana od vseh (samo spodnji rob ob pokrovu). Primerjava po zvočni moči med stranicami je pri ožemanju pokazala, da je zadnja stena najglasnejša.

The comparison between measurements of the partly and totally insulated machine in tumbling as well as during spinning show that we have succeeded in reducing the noise at all critical places. Additional insulation BORGERS has a much larger effect on the reduction of sound power of the appliance during tumbling - by 7.7 dB - than during spinning - by 2.5 dB. It seems that an essential element during spinning is a good insulation of the front wall. Special attention should be paid to the edges at the bottom of the appliance. All the sides of the appliance may be significant in terms of the origin of noise, so it is important that the whole appliance is insulated. This is true also for the back wall, which is not subject to such large vibrations as the front and side walls, but it can emit a high sound power. During measurements of the sound intensity of a partly insulated appliance the least insulated was the back wall (only the bottom edge near the cover). Comparison of the sound power from the sides during spinning has shown that the back wall is the loudest.



Sl. 6. *Ožemanje - delno izoliran stroj: zvočna moč po posameznih stranicah*
Fig. 6. *Spinning - partly insulated appliance: sound power by individual sides*



Sl. 7. *Ožemanje - v celoti izoliran stroj: zvočna moč po posameznih stranicah*
Fig. 7. *Spinning -totally insulated appliance: sound power by individual sides*

Razpredelnica 1. Zvočna moč naprave po posameznih spremembah
Table 1. Sound power of the appliance by individual changes

izolacija **insulation**	**zvočna moč pri mencanju v dB(A)** **sound power in tumbling in dB(A)**	**zvočna moč pri ožemanju v dB(A)** **sound power in spinning in dB(A)**
BORGERS debeline 15mm: delovna plošča in dno BORGES 15 mm thick: working panel and bottom	**57,3**	**70,3**
dodatno: izolacija na levi in desni stranici povišana do 600mm additional: insulation on the left and the right side raised to 600 mm	**52,6**	**69,9**
dodatno: leva in desna stran izolirana v celoti na dnu dodatno izolirani robovi additional: left and right side insulated in total and at the bottom additionally insulated edges	**49,6**	**67,8**

4 SKLEP

Hrupnosti pralnikov se samo z nadzorom vibracij ne da znižati do meje, ki jo dandanes terjajo zahtevni svetovni trgi. V članku smo najprej na kratko podali pregled teoretičnega modeliranja vibracij. Pri praktičnem zmanjševanju hrupnosti smo pred spremembo in po njej naredili podrobnejšo akustično analizo pralnika. To omogoča metoda meritve zvočne moči. Zvočna moč (aktivna komponenta gostote energijskega toka zvočnega valovanja) je vektor in z njim lahko dobimo informacijo o velikosti in smeri širjenja zvočne energije [7].

V nadaljevanju smo z izolacijo zniževali hrup na kritičnih mestih in smo se priporočenim vrednostim povsem približali. Tako se lahko pohvalimo, da so naši pralni stroji SUPER SILENT med najtišjimi na tržišču.

4 CONCLUSION

Vibration control alone is not sufficient to reduce the noise of washing machines to the level that is required by the demanding world markets of today. In this paper first a short overview of the theoretical vibrational modelling was given. During practical noise reduction a detailed acoustic analysis of the washing machine was conducted before and after the change, which is enabled by the method of measuring sound intensity. Sound intensity (active component of the density of the energy flow of the sound wave) is a vector delivering information about the value and direction of sound energy spreading [7].

Subsequently noise at critical points was being reduced by insulation and we reached the recommended values. Today we are proud to claim that our SUPER SILENT washing machines are among the quietest on the market.

5 SEZNAM SPREMENLJIVK
5 NOMENCLATURE

zvočni tlak	p	Pa, dB	sound pressure
zvočna moč	I	W/m^2, dB	sound intensity
moč	W	W, dB	power
sila	F	N	force
gostota	ρ	kg/m^3	density
hitrost	v	m/s	velocity

Zahvala

Avtor se zahvaljuje doc. dr. Mihu Boltežarju iz Laboratorija za dinamiko strojev in konstrukcij Fakultete za strojništvo Univerze v Ljubljani za pomoč pri pisanju članka.

Acknowledgement

Thanks are due to Doc.Dr. Miha Boltežar from Laboratory for Dynamics of Machines and Structures, Faculty of Mechanical Engineering, University of Ljubljana for the help in writing this paper.

6 LITERATURA
6 REFERENCE

[1] Boltežar M., N. Jakšić, A. Kuhelj (1998) Quantitative phase space analysis of the nonlinear planar oscillatory system. *Zeitschrift für Angewandte Mathematik und Mechanik*, 78(S1), 287-288.

[2] Jakšić N., Boltežar, M., Simonovski, I., A. Kuhelj (1999) Dynamical behaviour of the planar non-linear mechanical system – Part I: Theoretical Modelling. *Journal of Sound and Vibration*. (sprejeto v objavo/accepted for publication).

[3] Boltežar, M., Jakšić, N., Simonovski, I., A. Kuhelj (1999) Dynamical behaviour of the planar non-linear mechanical system – Part II: Experiment. *Journal of Sound and Vibration*. (sprejeto v objavo/accepted for publication).

[4] Fahy, Frank J. (1989) Sound Intensity, *Elsevier Science Publisher Ltd*., London.

[5] Beranek, L. (1988) Noise and Vibration Control, *Institute of noise control engineering, Washington.*

[6] Sound Power measurements (1992) Application Note 1230 *Hewlett Packard.*

[7] Holeček, N. (1992) Identifikacija virov hrupa in določanje zvočne moči, seminar podiplomskega študija, *Fakulteta za strojništvo, Ljubljana.*

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Prejeto:
Received: 11.1.1999

Sprejeto:
Accepted: 15.9.1999