WOOD RESEARCH
59 (1): 2014
123-136

MODAL ANALYSIS OF SOUNDBOARD OF THE UPRIGHT PIANO BY FINITE ELEMENT METHOD (FEM)

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(Received November 2011)

ABSTRACT

This work is engaged in the study of the change eigenfrequencies and eigenmodes of vibration of soundboard of the upright piano owing to change of material qualities (density, module of elasticity, spiro grain), change of geometry (slab thickness, ribs proportions, ribs number, bridges form) and the way of anchoring. Modal analysis was made by finite elements method in computer program ANSYS. Analysis model was arranged parametricaly by the help of script tongue APDL what allowed the construction of probabilistic design system sequence. The results describe influence of density and longitudinal module of elasticity of material with eigenfrequencies of board. Effect of spiro grain in cross plane appears like least relevant. Generally supposed influence of change of geometry and density with eigenfrequencies was more closery described for soundboard of upright piano. It follows from the research that values of eigenfrequencies grow with increasing of implasticity system what is incurred by mutual placing of ribs and blanks and anchoring. It comes to changes of eigenmodes of vibration especially with changes of fixation of soundboard.

KEYWORDS: Modal analysis, soundboard, upright piano, FEM, ANSYS.

INTRODUCTION

Musical instruments are systems with complicated physico-acoustic processes and the utilisation of numerical simulations is only possible option for complex description. Modal analysis of soundboard of string musical instruments firstly violins, guitars and pianos monitors eigenmodes of vibrations and eigenfrequencies relevant to them predicating the determination of quality of used material and its ability to vibrat in particular frequency districts.

Upright piano is musical instrument classing to string keyboards. It was developed early in the 18th century by vertical ordering of piano construction to fill less place in dwelling space. Like piano it is composed of multiplicity of parts participant in creation of tones. A box of upright piano has got decorative function and design function because it holds up and it saves the playing mechanism. The box is part of resonant body of the instrument together with the surround where the strings are fixed and the board carrying the sound to surroundings. That is why the used material has to fulfil the requirements of acoustic qualities and the dimensional stability of instrument.

The main acoustic component taking fundamentally a share in the creation of tone is sounding or soundboard. Tone is a harmonic sinuosity what is defined by waving propagation transmitting the sound energy in the material space. The function of soundboard is to splice the tons therefore the vibrations produced by string in the broad scale of frequencies (Wogram 1990). The scale of present classical upright piano is 88 tons, from A_1 to c^5 (7 and ¼ of octave).

The special requirements on the part of material quality are posed on soundboard of string musical instruments. The highest requirements are posed on resonance wood used by violin-making. They are high for upright piano-making too however the demands for upright pianos go down because they aren´t instrumental towards especially concert function and the structure of whole musical instrument allows shallow deviations from high standard. Soundboard is made mainly from whitewood (*Picea abies* L.).However the acoustic qualities differ tree by tree and so the big attention is dedicated to the research of this material. Bucur (1995) realized a research in the section of acoustic features of wood. Outside tension in material is raised by outside stress (press of sound-wave) and it has got an influence with its proportional deformations (the deflexion of soundboard). Kubojima et al. (2006), Holz (1981), Caniato et al. (2007), Carter and Achim (2009) e.g. experimentally found out the relationship between the module of elasticity and the density.

By means of modal analysis it is possible to find out characteristics of structure and used materials which we can replace by the similar materials according to the results. Above all we can optimize a form of the structure by means of it. Fletcher and Rossing (1998) describe physico-acoustical principles of the string musical instruments in detail. They give a detailed description of the physics of musical instruments and they are referencing Nakamura (1983) who studied the eigenmodes of vibration and eigenfrequencies of the soundbouard of the upright piano without the ribs. Wogram (1990) was engaged in the experimental modal analysis of the upright piano. He monitored the relation of the soundboard and strings. Suzuki (1986) studied eigenmodes of vibration of the soundboard of the upright piano by means of the numerical analysis and together with Suzuki and Nakamura (1990) they describe the acoustics of the whole upright piano. Nakamura (1993) describes the parameter of vibrations of the soundboard of the upright piano by the method of numerical analysis. The slab thickness 6.5-9.5 mm is standardly used. Suspension of cuts is the next factor affecting the eigenfrequencies. Wogram (1990) monitors the effect of slab thickness let us say height of cut of ribs and the number of ribs on the eigenfrequencies. He comes to the conclusion that the restriction of the ribs relates to the situation when the height of the original number of ribs was reduced by the quarter.

The analysis using of numerical simulations by means of the finite element method showed as the equivalent methods to the experimental methods in comparison of the received results. The works of Kindl and Wang (1987) or Berthaut et al. (2003) and others demonstrate it. Giordano (1997) demonstrates the simplified orthotropical model of the board with ribs describes the basic characteristics. Berthaut (2003) modelled the exact finite-elementary model of the resonance board of the piano and compared the received modal characteristics with the experimental modal analysis of real board. He used this method to the optimizing of the form of the resonance board of the piano, too. However there was not involved the overpressure of strings here which has got an significant influence on the modal characteristics. Mamou-Mani et al. (2007) dealt with it. They searched the load of resonance board by strings using finite element method and its influence with vibrations of resonance board with application of prestress analysis. They viewed the effect on ribs, bridges and surround. Their experiment analyses toughness of by surround caused construction as an significant factor working size of eigenfrequencies. Ortiz-Berenguer et al. (2008) make use of finite-elementary model of resonance board of Steinway piano to research of relevancy of the shape or dimensions to ability to vibrate. Askenfelt and Jansson (1990) dealt with the system from key over hammers to strings. They experimentally evaluated the quality of sound and vibration of string. Askenfelt together with Chain (1994) dealt with numerical simulation of the same problem. Tippner (2007) except the effect of prestress evocated by the overpressure of strings deals with the temperature-moisture effect on dynamic characteristics of resonance board of Pertof piano. Moore and Zietlow (2006) recognize by the help of inferometer the working forms of resonance board of the upright piano and piano and they create the computer model for the numerical simulation at the same time. Only they compare eigenmodes of resonance board of the upright piano during the stress by strings with eigenmodes of resonance board without the stress. They watched a big influence with the stress of strings especially for the first eigenmodes and size of the relevant frequency.

The aim of this work is to prepare a finite-elementary model of the sound board of the upright piano and to use it for a description of eigenfrequencies and eigenmodes of vibration by the help of numerical modal analysis. The geometry and material of the board will be identified by parameters and on the basis of some simulations the alternatives of the construction of the board will be compared from the view of the material structure and anchoring in the instrument. The model will be enriched with the construction of treble and bass bridge and ribs. Their influence with eigenfrequencies and eigenmodes of vibration will be watched.

MATERIAL AND METHODS

For the making of the numerical model of the sound board of the upright piano was used ANSYS Mechanical APDL taking the finite element method (FEM). This system is very wide-spread. It disposes of the quality certificate ISO 9001 and it is often considered as reference system. Kohnke (1998), Nakasone (2006), Madenci and Guven (2006), Moaveni (2008) describe its basic using in a graphical world. The submission of problems can be easy defined by means of scripting language APDL (Ansys Parametric Design Language).

The production of computing methods lies in the definition of geometry, material, netting and marginal conditions in preprocessing, submission of calculation and the calculation itself in solution and processing of numerical or graphical results in postprocessing. The values of dimensions were parametrized for the case of watchingzhe influence of geometry on the size of its own frequencies and shapes of vibration.

The sound board of the upright piano is in crosscut so wedge-shaped that its thickness grows up. There were compared the thicknesses 6.5-9.5 mm (standard) and 5.5-7.0 mm. The model was completed on the basis of actual projects of construction of soundboards of upright Petrof pianos with the cut in bottom of board which sets free the board from the surround on this place. Delimited values are especially depth let us say height of cut, length of cut and radius of plumping in corners of cut. The model of the soundboard is filled out with bridges (treble and bass) and ribs according to real dimensions with the standard parameters of lengths, latitudes ect. There were applied three types of boards with marks SB_1, SB_2 and SB_3 for the comparing of eigenmodes of vibration and eigenfrequencies. SB_1 is board with thickness of 6.5-9.5 mm without bottom release with slope of blanks 400 and eleven profile ribs which are saved upright to direction of blanks. There are also two prismatic ribs in the left bottom and right upper corner of board which are saved parallel with blanks. The board marked SB_2 differs in release at the bottom border and board SB_3 has got in addition to it horizontally saved rib with length respondent with length of cut closely over cut. On the board marked SB_1 there is watched the influence of the change of number and position of ribs according to vibrating plane of board and their effect on eigenmodes of vibrations and size of eigenfrequencies.

For resonance wood for soundboard making are posed such claims that we can consider the wood what generally shows characteristics of anisotropic material in cylindrical reference frame in this case for ortotropic in Cartesian reference frame (Tippner 2007) what fundamentally simplifies definition of material for calculation in ANSYS program. Providing small deformations which we can expect for stress of soundboard with vibration and overpressure of strings we can use linear-elastic model Hook rule for the describing of mechanical response. Tippner (2010) sums up characteristics of resonance wood inspired by the authors like Green et al. (1999), Bucur (1995). According to it there are chosen values of density of wood from 420 to 460 $kg.m^{-3}$ and module of elasticity in longitudinal direction corresponding with them. There was fixed another value of density to each blank and corresponding calculated longitudinal module of elasticity. Two left over normals and three shear modules of elasticity are calculated through constants (proportions between separate modules) according to Green et al. (1999); Poisson numbers are constant for all materials (Green et al. 1999). Material constants for ribs are the same as for the soundboard. The bridge is beech and values of constants are assumed (Bucur 1995 cit. Hearmon 1948). Probabilistic analysis by means of probabilistic design system (PDS) allows wider rating of influence with material parameters. PDS allows the use of pseudo-random generating of numbers for parameters by method Monte Carlo. There is used the Gauss distribution of values for material constants for which are the arithmetic average and standard deviation as the entrance parameter. Parameters for diagonal grain of material from geometry axes of resonance blank were included into this analysis. Then density and normal module of elasticity too.

Especially the anchoring of the model (limitation of ranks of free displacement to border of place) is edge condition at modal analysis. The confrontation of eigenmodes of vibration and eigenfrequencies of soundboard in musical instrument is possible at some possible ways of anchoring.

To find out eigenmodes of vibration and eigenfrequencies there is chosen Block Lanczos´s method defined just for these types of calculations (Madenci 2006). The number of output values (the number of modes) is at least for all causes of geometry. The values of the first eigenfrequencies and forms of following at least five eigenmodes are important. Probabilistic analysis –the determination of the effect of different parameters on the size of eigenfrequencies is assured by probabilistic analysis (Probablistic Design) which by chance fills up the parameters of predefined deviation values. By these parameters is density of blanks, diagonal grein and modules of elasticity both in all three planes. Ability of board to vibrate is compared by watching of participating factor of vibrating board substance along axis Z (here: the quotient of board substance peeking upright to board plane). This method is acceptable for basic evaluation of relevance of eigenmodes of vibration obtained by the modal analysis.

RESULTS AND DISCUSSION

Thickness influence

The board influence belongs to the parameters where there was viewed the effect on eigenfrequencies and eigenmodes of vibration. The original shape of soundboard has a wedge-shaped cut so the soundboard becomes wider towards up. Usual proportions of board thickness are in lower part 6.5 and upside 9.5 mm. Diagonal way of cuts has got deviation 400 from vertical cant of soundboard (it refers to deviation of Petrof pianos used at that time).

Tab. 1: The eigenfrequencie at the change of thickness of soundboard with the slope of 40°.

No. of FRQ	Frequence [Hz]	
	SB 5.5-7	SB 6.5-9.5
1	110.1	122.5
2	148.2	177.2
3	207.6	255.1
4	267.8	316.3
5	291.5	349.9
6	320.5	384.3
7	367.1	451.2
8	395.0	485.7
9	456.2	563.2
10	484.3	595.4

The dates of results are worked in Tab. 1 and in the graph in the Fig. 1. It shows the difference is small in values at the first eigenfrequencie and it still increases at higher eigenfrequencies with increasing order of mode. The soundboard with thickness of 6.5-9.5 mm has got stronger differences between consecutive values of eigenfrequencies and the same wrote Askenfelt (1990) and Wogram (1990). At first the difference at values is approximately 11 %, at the tenth mode the difference is already 19 %. It means the soundboard with thickness of 5.5-7.0 mm will vibrate in the middle frequencies more because here it will have higher substitution of eigenfrequencies thanks to less trend of development. The difference of whole tone is in value of the first eigenfrequencie between tested boards.

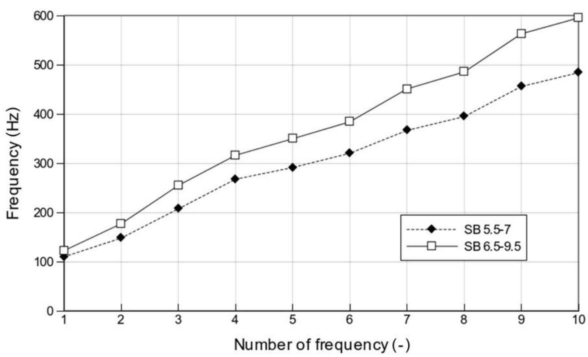


Fig. 1: Size comparison of eigenfraquencies at the change of thickness of the soundboard.

Ribs influence

The eigenmodes of vibration of the separate soundboard and the soundboard with bridges respect the direction of cut support. The eigenmodes of vibration change after the adjunction ribs to the soundboard – they follow neither the support direction nor ribs direction but the system as complex. Fig. 3 shows the 1st, 5th and 10th eigenmodes chosen on the ground of obvious example of change of dynamical behavior of soundboard. The eigenmodes are very similar like eigenmodes according to Nakamura (1990) and Wogram (1990). Values of eigefrequencies are little bit diferent because of thickness and shape of soundboard. The eigenfrequencies of soundboard with bridges and ribs are higher compared to the soundboard with only ribs and also debit frequencies grows with growing order of mode (Fig. 2).

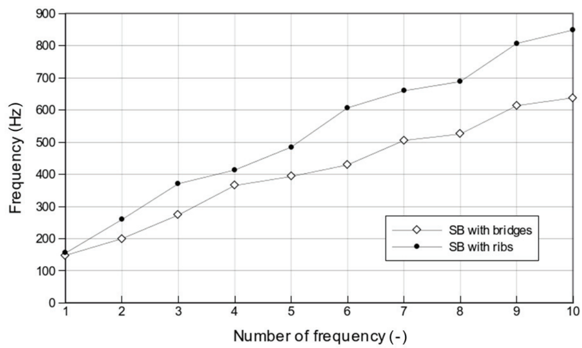


Fig. 2: Ribs influence on eigenfrequencies of soundboard (with bridges) compared to the soundboard with only bridges.

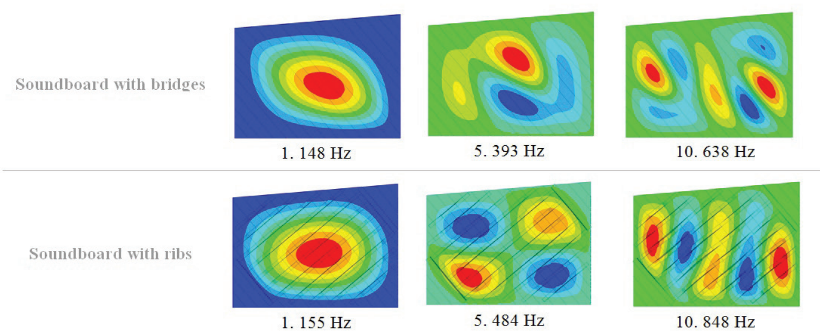


Fig. 3: Ribs influence on the eigenmodes of vibration.

Probablistic analysis of the influence with material character

The probabilistic analysis shows mutual parameters influencing values of the first eigenfrequencie of soundboard with board thickness of 6.5-9.5 mm, blanks slope 400 and parameters of ribs and bridges on the graph (Fig. 4). Density of resonance blanks has got maximum influence on eigenmodes (Fig. 5), it stands the value of the first eigenfrequencie of soundboard sinks with growing density. The value of elasticity module has an important part in the longitudinal direction when the value of eigenfrequencie grows with the growing value of elasticity module (Fig. 6). This results agree with Kubojima (2006). Elasticity module is not important in the tangential direction and the diagonal grain from the longitudinal and radial geometry axis of blank, too.

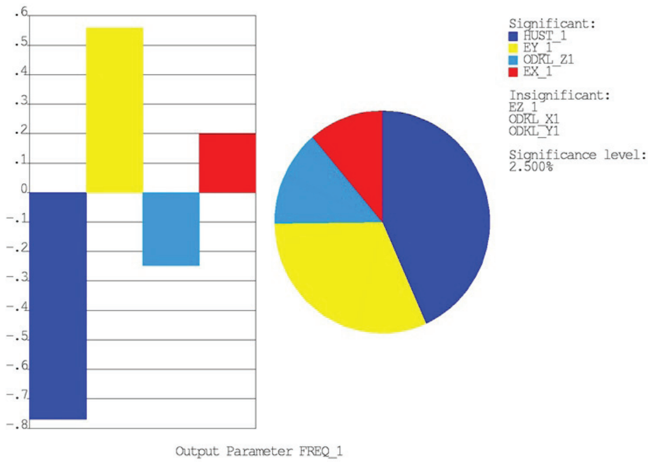


Fig. 4: Results of probabilistic analysis for fisrt eigenfrequency, parametres are material properties. HUST_1 – density, EX_1,EY_1,EZ_1 – normal modulus of elasticity (X,Y,Z matches R,L,T), ODKL_X1,ODKL_Y1,ODKL_Z1 – deflection of anatomical axes (X,Y,Z matches R,L,T).

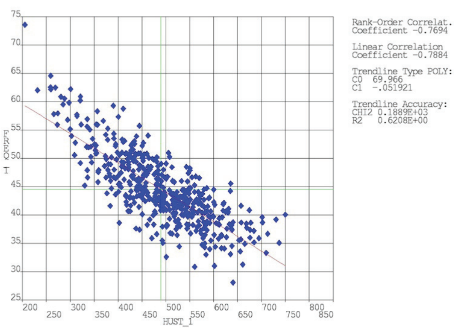


Fig. 5: Relation between value of first eigefrequency and density of resonance cuts.

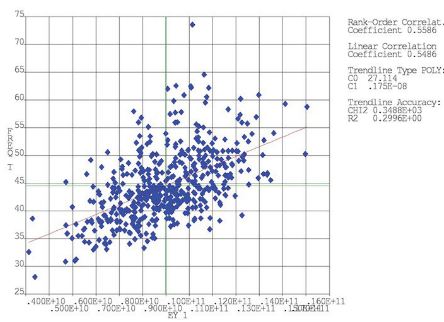


Fig. 6: Relation between value of first eigefrequency and longitual modulus of elasticity of resonance cut.

Influence by detente of cut

According to picture Fig. 7 SB_1 shows a better ability at the fourth and eighth eigenfrequencies. SB_2 vibrates the best what is in virtue of the slackness of anchoring in the area of bottom cut which is braced by a horizontal rib. We can say SB_3 notes the least deviations but the sixth eigenfrequencie is the exception. The ratio of participating factor is interesting at all boards in the unequal frequencies. The values for all three types of soundboard are largely close here (except the third mode). The development trend of eigenfrequencies is in the Fig. 8. It follows from it that the values of eigenfrequencies grow with growing density of anchoring of board (Tab. 2).

The effect of rib stiffening the slackness of soundboard on eigenfrequencies is inexpressive; peek of substance falls down because the system is braced. Values of the first, second and fourth eigenfrequencies are comparative for all types of boards but at the second and fifth there is the marked difference between SB_1 and left two boards. However eigenmodes of vibration are marked differently (Fig. 9). Values of freqencies depends on boundary conditions (Mamou-Mani et al. 2008).

Tab. 2: Values of the first ten eigenfrequencies for SB_1, SB_2 and SB_3.

Frequence (Hz)		
SB_1	**SB_2**	**SB_3**
155.3	109.9	117.7
259.2	224.4	221.3
370.5	237.0	244.6
413.1	382.0	389.1
483.9	407.0	411.2
606.6	472.7	452.9
659.0	554.8	566.2
688.2	620.7	632.1
806.3	669.0	671.9
848.7	764.8	748.0

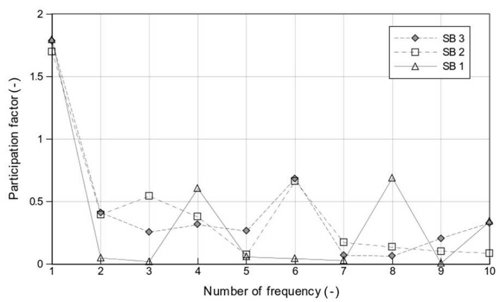


Fig. 7: Comparison of participating factors of boards SB_ 1, SB_2 and SB_3.

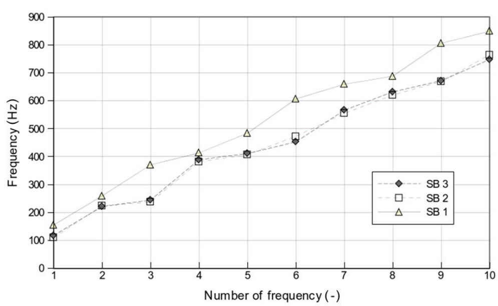


Fig. 8: Development trend of eigenfrequencies at three types of lightening/bracing of soundboard.

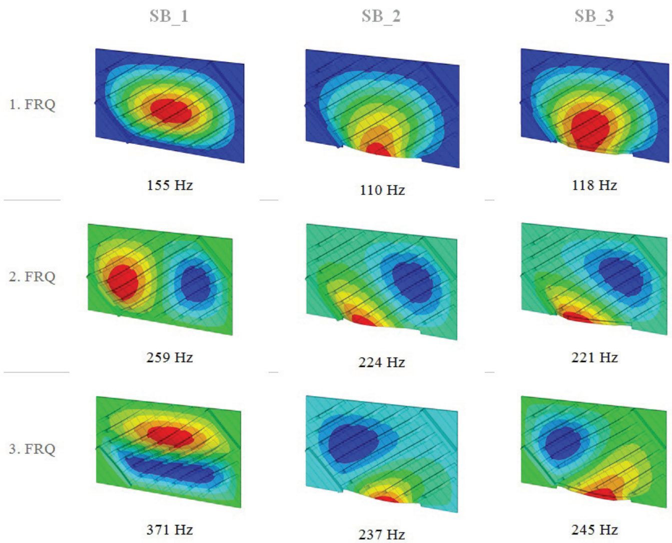


Fig. 9: The first four modes of soundboards (from left) SB_1, SB_2 a SB_3 with values of eigenfrequencies.

Influence of the number and placing of ribs

The soundboard of the upright piano is usually settled with eleven ribs. They are mainly put crosswise to the direction of cuts placing on the ground of the bracing of soundboard in the regular distance from each other. Describing of it how the change of number and placing of ribs influences eigenfrequencies and eigenmodes of vibration is the scope of this chapter. There were chosen four types of placing. SB_1 is marked as the 1st type, the soundboard with detracted even-numbered ribs is the 2nd type; there are kept two up and two down outer ribs and two ribs in the middle of board for the 3rd type. As 4th and 5th marked ribbing types steps down the number of ribs for seven and they are placed according to the vibrated area of soundboard. It is evident from results that all types have eigenfrequencies and eigenmodes of vibration very similar (Tab. 3). The third mode of vibration is exception and especially in case of the third type of ribs placing. The graph on the Fig. 10. shows the comparison of participating factor of soundboard with different types of ribs placing. It shows here that the part of vibrating substance at the soundboard with original ribbing is higher in the first, fourth and eighth eigenfrequencies. The reason is the ribs placing involving at the given eigenmodes of vibrate and their vibrate substance is included in the calculation of participating factor. The 3rd of ribs placing contrasts the most with values of vibration. For the next tests It would be right to keep the number of ribs and to change their placing to support of the definite eigenmodes so not to place ribs in the place of their peaks but to put them rather into nodal lines. As well the thickness or height of ribs because they go towards the density of system and it also has an effect on the size of eigenfrequencies or vibrating substance like said Wogram (1990) and Askenfelt (1990), too.

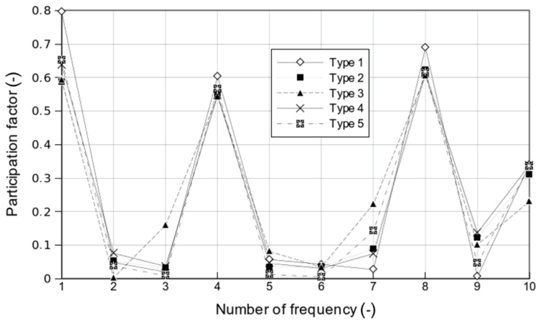
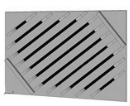
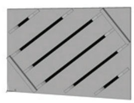
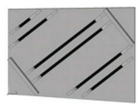
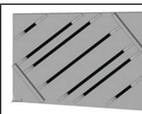
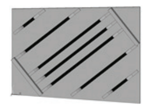


Fig. 10: Participation factor of five types of ribs placing on the soundboard.

Tab. 3: Influence of placing ribs on a modal properties of upright piano soundboard.

TYPE	 **1. type**	 **2. type**	 **3. type**	 **4. type**	 **5.type**
WEIGHT	5.384 kg	4.520 kg	4.557 kg	4.698 kg	4.744 kg
1. FRQ	155 Hz	158 Hz	160 Hz	159 Hz	154 Hz
2. FRQ	259 Hz	259 Hz	258 Hz	258 Hz	260 HZ
3. FRQ	371 Hz	258 Hz	375 Hz	379 Hz	378 Hz
4. FRQ	413 Hz	407Hz	411 Hz	409 Hz	412 Hz
5. FRQ	484 Hz	489 Hz	486 Hz	492 Hz	484 Hz
6. FRQ	607 Hz	594 Hz	594 Hz	596 Hz	602 Hz
7. FRQ	659 Hz	651 Hz	641 Hz	654 Hz	655 Hz
8. FRQ	688 Hz	706 Hz	710 Hz	700 Hz	701 Hz
9. FRQ	806 Hz	809 Hz	783 Hz	809 Hz	812 Hz
10. FRQ	848 Hz	822 Hz	834 Hz	829 Hz	833 Hz

CONCLUSIONS

For the soundboard of upright piano with the treble and bass bridge and ribs was created the finite-elementary model in the environment of the program ANSYS. The parametric model respects difficult geometry of board, robs and bridges, it includes the linear-elasticity substance model defined separately for each part (including the possibility of the introduction of diagonal grain) when engineering constants depend on one another and with the density. This model was used for modal analysis. There were compared two thicknesses of soundboard, modal characteristics of separate soundboard too, soundboards with bridges and with ribs. There was watched the influence of different way of anchoring of soundboard watching the improvement of its emitting by its slackness or changes of ribbing. The model was remitted to what-if-analysis.

It showed at the judging of thickness influence that eigenmodes of vibration don´t change but the soundboard with less thickness has got more reasonably increase of eigenfrequencies values . it means it will be flash better in the frequency area of upright piano scale. The increasing of system toughness by ribbing goes to marked change of eigenmodes of vibration and eigenfrequencies of board from 145 to 155 Hz. Changes of eigenribbing influence modal characters insignificantly. For example it goes to change of eigenfrequencies about round 2 % by reduction of ribs number from eleven to six while holding of ribs dimensions. The influence of anchoring change (the by bottom cut latitude) caused marked change of eigenfrequencies and eigenmodes of vibration. Values of eigenfrequencies went down and the centre of vibration moved from the middle of system to the bottom flowing area. The final effect is the reinforcement of undertones. What-if-analysis evaluating the effect of elasticity modules, density and diagonal grain in the wood on the size of eigenfrequencies showed the most marked effect of density and longitudinal elasticity module and less marked effect of radial elasticity module. The deflection of tangential direction from plane of soundboard is significant only in bounds overhanging in common use spiro grains in blanks, the other watched parameters aren´t significant. As compared to experimental methods of modal characteristics finding this work general agrees with their results.

Results of modal analysis makes for watching of modal characteristics changes depending on the change of different parameters. The plan is to increase the performance of soundboard in the area of low and high frequencies consequently the performance increasing of upright piano while the tone quality holding. The finale-element model will be used for next analysis types examining characteristics of system as for example the harmonic analysis finding the amplitude of system, static analysis serving to describ of stress-deformation characteristics or transient describing the vibration in the time let us say the afterglow of soundboard.

ACKNOWLEDGMENT

Supported by the European Social Fund and the state budget of the Czech Republic, project "The Establishment of an International Research Team for the Development of New Wood-based Materials" reg. no. CZ.1.07/2.3.00/20.0269.

REFERENCES

1. Askenfelt, A., Jansson, E.V., 1990: From touch to string vibrations, in five lectures on the acoustics of the piano. Edited by A. Askenfelt (Royal Swedish Academy of Music, Stockholm), 64: 39-57.
2. Berthaut, J., Ichchou, M.N., Jézéquel, L., 2003: Piano soundboard: Structural behavior, numerical and experimental study in the modal range. Applied Acoustics, 64(11): 1113-1136.
3. Bucur, V., 1995: Acoustics of wood. Boca Raton: CRC Press, 284 pp. ISBN 0-8493-4801-3.
4. Caniato, M., Favretto, S., Lucchini, E., 2007: A new approach for the characterization of the resonance wood. 19th International Congress on Acoustics, Madrid, 6 pp.
5. Carter, P., Achim, A., 2009: Assessing the potential of acoustic tools to predict sawn batten stiffness in Sitka Spruce. The Research agency of the Forestry commission.
6. Chaigne, A., Askenfelt, A., 1994: Numerical simulation of piano strings I., A physical model for a struck string using finite difference methods. Journal of the Acoustical Society of America, 95(2): 1112-1118.
7. Fletcher, N.H., Rossing, T.D., 1998: The physics of musical instrument. 2nd edition, Springer Science and Business Media, Inc., 756 pp. ISBN 0-387-98374-0.

8. Giordano, N., 1997: Simple model of a piano soundboard. Journal of the Acoustical Society of America, 102(2): 1159-1168.
9. Green, D.W., Winandy, J.E., Kretchmann, D.E., 1999: Mechanical properties of wood. Wood handbook: Wood as engineering material. Madison, Wisconsin, USA, Forest product laboratory. Pp 4-1 to 4-45.
10. Holz, D., 1981: Zum Alterungsverhalten des Werkstoffes Holz – einige Ansichten, Unterschungen, Ergebnisse. Holztechnologie 22(2): 80-85.
11. Kindel, J., Wang, I., 1987: Vibrations of a piano soundboard: Modal analysis and finite element analysis. Journal of the Acoustical Society of America, 81: S61-S61.
12. Kohnke, P., 1998: ANSYS – Theory reference. Canonsburg, PA, USA, ANSYS, Inc. 965 pp.
13. Kubojima, Y., Tonosaki, M., Yoishihara, H., 2006: Young´s modulus obtained by flexural vibration test of wooden beam with inhomogenity of density. The Japan Wood Research Society. Pp 20-24.
14. Madenci, E., Guven, I., 2006: The finite element method and applications in engineering using ANSYS. New York: Springer, 686 pp. ISBN 0-387-28289-0.
15. Mamou-Mani, A., Frelat, J., Besnainou, C., 2008: Numerical simulation of a piano soundboard under downbearing. Journal of the Acoustical Society of America, 123(4): 2401-2406.
16. Moaveni, S., 2008: Finite element analysis: Theory and application with ANSYS. 3rd edition. Upper Saddle River, N.J.: Pearson Prentice Hall, 861 pp. ISBN 978-0-13-241651-1.
17. Moore, T.R., Zietlow, S.A., 2006: Interferometric studies of a piano soundboard. Journal of the Acoustical Society of America, 119(3): 1783-1793.
18. Nakamura, I., 1993: Vibrational and acoustic characteristics of soundboard. Journal of the Acoustical Society of Japan, 16(6): 429-439.
19. Nakasone, Y., Yoshimoto, S., Stolarski, T.A., 2006: Engineering analysis with ANSYS software. Amsterdam: Butterworth-Heinemann, 456 pp. ISBN 0-7506-6875-X.
20. Ortiz-Berenguer, L.I., Casajus-Quiros, F.J., Blanco-Martin, E., Ibanez-Cuenca, D. 2008: et al., 2008: Modeling of piano using FEM simulation of soundboard vibration. Acoustics 08 Paris, France. Pp 6251-6256.
21. Suzuki, H., Nakamura, I., 1990: Acoustic of piano. Appl. Acoust. 30(2-3): 147-205.
22. Suzuki, H., 1986: Vibrational and sound radiation of a piano soundboard. Journal of the Acustical Society of America., 80(6): 1573- 1582.
23. Tippner, J., 2007: Finite-element model and modal analysis soundboard of grand piano (Konečně-prvkový model a modální analýza rezonanční desky klavíru). Acta Mendelovy zemědělské a lesnické univerzity v Brně. sv. LV,. 4: 111-118, ISSN 1211-8516 (in Czech).
24. Tippner, J., 2010: Numerical simulation of grand piano soundboard.(Numerická simulace rezonanční desky klavíru). PhD. Thesis, Mendel University in Brno (in Czech).
25. Wogram, K., 1990: The string and the soundboard. In: Five lectures on the acoustics of the piano. Edited by Askenfelt.

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