Acoustic and physico-mechanical properties of spruce timber: influence of differently intensive pruning

O Antonov1,2, A Dobrovolsky2, E Kuznetsov2

1Saint Petersburg Forestry Research Institute, 21 Institutsky prospect, Saint Petersburg, 194021, Russian Federation
2Saint Petersburg State Forest Technical University, 5/U Institutsky pereulok, Saint Petersburg, 194021, Russian Federation

1E-mail: woodfm@mail.ru
2E-mail: alexander-83@yandex.ru

Abstract. The work studies the physico-mechanical properties of wood from the stands of Norway spruce (Picea abies (L.) Karst.), formed after pruning of various intensity. It was revealed that the high-intensity pruning in 23-year aged spruce stands (5-6 upper live branch clusters were left) led to a significant increase in the density of wood (by 15.6%) for trees with diameter larger than average in 3 years after. The removal of live and dry branches of lesser intensity does not affect the density of the wood. The wood formed as a result of 60 years of cultivation after pruning has quite high physical and mechanical properties: the compressive strength along the fibers is 51.6±1.02 MPa compared to reference value of 44.5 MPa; and the larger impact toughness (0.68±0.045 kgf/cm²) than the reference value (0.40). It has been established that wood formed over 60-year cultivation after pruning has resonant properties: the average acoustic constant is 11.4 m²/kg×sec., while the optimal value of this indicator for the use of this wood in the music industry is more than 12 m²/kg×sec. It has been concluded that pruning combined with rational stand density makes it possible to produce wood with acoustic properties.

1. Introduction
One of the main goal of proper forestry is to increase the quality productivity of plantations in the process of intensive forest growing. This applies to improving the quantitative and qualitative parameters of the entire stand and each tree separately, as well as the properties of the produced wood [1]. This is the main criterion for successful work of various branches of the timber industry (logging, woodworking, furniture, pulp and paper production, etc.). Indicators such as knotty, wood density, fiber length, etc. affect the quality of the final product and its cost [2].

The art of creating musical instruments demands craftsmanship of an instrument-maker and the availability of high-quality wood. The legendary violin-makers of the 16th – 17th centuries (Bertolotti, Amati, Guarneri, Stradivari, and others) chose spruce wood for their instruments as it offers the best acoustic radiating properties and is distinguished by its comparative lightness, substantial resilience and specific uniformity of texture, which, by more than 90%, is made up of tracheides, i.e. narrow fibrous cells whose length is in large excess over their width.
Wooden musical instruments, especially the guitar, violin, alto, cello, double-bass, piano, are sophisticated products made of wood and characterized by different designs, constructions, dimensions, used materials, fabrication techniques and equipment. An important part in these instruments is assigned to an acoustic radiating element or a so called soundboard. That, for its intended purpose, performs multiple different functions. This board is made as an anisotropic plate with an intricate shape and a variable cross-section. It is furnished with stiffening ribs possessing different mechanical characteristics. Apart from the function of acoustic amplification, the soundboard plays yet another important role – to make the tone more refined and instill it with an appropriate gradation, clarity and completeness [3]. Music craftsmen call the soundboard the soul of a musical instrument when discerning between successful and unsuccessful instruments.

The wood of long-term keeping (upward of 50 years) is known as possessing the best acoustic characteristics. During the senescence the content of hemicelluloses in the wood is changing so that it becomes more resistant to thermal and humidity effects, and musical instruments made of this wood possess more stable acoustic characteristics. In instrument-making, use is made of wood that is more resistant to acoustical irradiation and has the minimum internal friction. This is so called sounding or resonant timber, which is characterized by a sound propagation constant, or radiation constant.

The maximum sound propagation constant is typical for coniferous wood and, first of all, for such species as spruce, silver-fir, Caucasian fir, and Siberian pine, amounting to about 12 m^4/kg×sec [3]. Blanks of resonant wood, according Russian classification standards of String musical instruments (TU 205 RSFSR 08.922-91), have to meet a number of requirements: - the width of annual rings must be within the range of 1 to 4 mm, and the summer-wood contained in them must not exceed 30% (no more than 20% for concert grand pianos); - the resonant wood must have an even texture and be free from knots and structural defects, especially eccentricity and twistiness. Spruce wood is the best to meet the above requirements and mainly used for making bow instruments and plucking instruments. The outward appearance peculiar to the sounding spruce woods, first of all, attributable to its fineness and evenness of annual rings’ structure. The narrower rings the wood has the more resilient it is and more capable of resonating with high frequencies. Apart from this, the spruce wood, as compared to other coniferous species, is characterized by more pronounced regularity of the relation between the width of annual rings, on the one hand, and the specific density and resilience, on the other hand [3]. Resonant small planks have to meet the requirements of so called radial cutting where the saw-cut plane is perpendicular to the direction of annual rings.

A biological property of spruce is associated with its poor self-pruning. Self-pruning is one of mandatory functions of the crown which is thinned out over its total length, but the most intensive dieback of branches takes place in its lower part [4]. All wood species have the following sequence of pruning stages: the dieback of branches, the deterioration of branches, the falling off, and the regeneration. Spruce is characterized by rather an intensive dying-off, but the process of deterioration takes a period of some length. For example, some authors [5, 6] maintains that spruce branches fall off within the span of 70 years in rare cases this period can be from 150 to 200 years. Such factors as the high tar-content in spruce branches, their resistance to wood-destroying fungi and chemicals prevent spruces from more rapid falling off. By the time period of 100 years, the completely cleaned area hardly reaches 2 m, but, due to the proximity of regenerated branches to the trunk surface, it is practically impossible to produce a high-grade timber. Therefore, the problem of obtaining high quality wood is quite relevant.

The most effective way of improving the quality of wood being grown lies in pruning which is not widely used in Russian silvicultural practice. The density as an integral indicator of wood quality determines the majority of its physical and mechanical properties [7]. As a high degree of correlation exists between the density and the above properties, every decrease in the density implies a decline in physical and mechanical properties, and vice versa. Apart from this, a reduced density of wood is associated (for coniferous wood) with increased branchiness and determines a high degree of vulnerability of trees exposed to heart rots [7].
Reasearches focused on the high-quality wood cultivation, including using pruning regimes, were performed by a number of authors [8, 9, 10]. At the same time there are still no data about resonant properties of the wood formed under the influence of pruning.

The aim of this work was to study the properties of wood from the stands of Norway spruce (Picea abies (L.) Karst.), formed after pruning of various intensity.

2. Materials and methods

For the study we used stands of Norway spruce planted in 1956 in the Taitskoye forest (the Gatchinskoy forest, compartment 28, allotment 2, Leningrad region, Russia). In order to develop a technology for growing high-quality branchless wood, experiments were started in 1985 on lopping-off of live and dry branches on stands with different density within permanent study areas (PSA 157-160, Table 1). The branches were removed in a single action at a height of up to 6.5 to 7.5 m in trees of all categories of thicknesses (figure 1). In the meantime, the intensity of pruning amounted to 35-41% of the total length of the crown in medium-sized and small trees and to 28% in large trees.

Then we studied the stands of Norway spruce planted in 1967 in the Susaninskoye forest sub-district of the Vyritskoye forest district (compartment 68, allotments 19, 20, 21) (PSA 105, 2, Table 1). In 1986, large and medium-sized trees were subjected to the high-intensity pruning of live and dry branches (50-60%), but 5-6 upper live branch clusters were left. In doing so, the pruning height amounted to 4 to 5 m.

| Forest district | Taitskoye | Taitskoye | Taitskoye | Taitskoye | Susaninskoye | Susaninskoye |
|----------------|----------|----------|----------|----------|--------------|--------------|
| Treatment      | Pruning  | Pruning  | Pruning  | Control  | Pruning      | Control      |
| Quantity of permanent study areas | 157 | 158 | 159 | 160 | 105 | 2 |
| Year of establishment | 1956 | 1956 | 1956 | 1956 | 1967 | 1967 |
| Area, ha       | 0.23     | 0.17     | 0.14     | 0.07     | 0.15         | 0.12         |
| Density, st/ha | 2600     | 2000     | 1400     | 2400     | 3800         | 3800         |

Branches were removed up to the height of 2.0 m with the use of handsaws. Above this level they were removed with a special tool for trimming branches, designed by SPbNIILH (figure 1). This work was done over the period of May to October. Wounds were performed flush with the trunk surface so that the bark was left undamaged.

Under study was also the experiments established in 1929 by Prof. A.V. Davydov and Z.Ya. Solntsev (SPbNIILH, Russia) on pruning dry branches in the Kartashevskoye forest (Siversky forest belonging to Saint Petersburg Forestry Research Institute, Russia). Experimental work was performed in Oxalidaceae type of spruce forest (the growth class of Ia, 60 years old). Pruning was done up to height of 7 m.
To study the physico-mechanical and acoustic properties of wood, 8 experimental and 4 control of 120 years aged trees were cut down (figure 2). This study dealt with the reference wood density \( \rho_b \) that showed the quantity of absolutely dry stuff in a cubic unit of a freshly felled tree or a sample under study. The reference density was determined by measuring the buoyant force acting upon a submerged body:

\[
\rho_b = \frac{m}{V_{max}}, kg/m^3
\]  

(1)

where \( m \) – the sample’s mass in an absolutely dry state; \( V_{max} \) – the sample’s volume at a humidity that exceeds the limit of wood hygroscopicity (30%).

The number of samples (figure 3) studied was 20-25 cores from each permanent study areas. Tests for ultimate compressive strength along the grain of wood were performed using the samples sized 2x2x3 cm on machine for mechanical testing (AVK, Budapest) with the capacity of 5,000 kgf. Prior to the tests, the exact dimensions of the samples were established (up to 0.01 cm). The ultimate compressive strength was calculated by formula:

\[
\sigma_w = \frac{P_{max}}{a_w \times b_w}, kgf/cm^2
\]  

(2)

where \( \sigma_w \) – the ultimate compressive strength along the grain of wood in wet state; \( P_{max} \) – the maximum load endured by the sample, kgf; \( a_w, b_w \) – lateral dimensions of the sample, cm.

As humidity of the wood samples \( W \) during the testing was equal to 8.0%, the ultimate compressive strength \( \sigma_w \) was reduced by formula (3) to the standard value of \( \sigma_{12} \):

\[
\sigma_{12} = \sigma_w \times [1 + \alpha(W - 12)], kgf/cm^2
\]  

(3)
where $\sigma_{12}$ - the compressive ultimate strength of wood at 12% humidity and $W = 8\%$; $\alpha (=0\,04)$ was an adjustment factor.

During the deflection tests there was determined the impact viscosity that specifies the ability of wood to absorb the work without being destroyed. For the testing, use was made of an impact testing machine with a stored energy of 10 kgf = 100 J. The impact viscosity was calculated by formula:

$$ A_w = \frac{Q}{bh}, \text{kgf/m/cm}^2 $$

(4)

where $A_w$ - the impact viscosity; $Q$ – the work to the sample’s failure at a given value of humidity; $b$ – the sample’s width, cm; $h$ – the sample’s height, cm.

The impact viscosity $A_w$ was reduced to the standard value of $A_{12}$ by formula:

$$ A_{12} = A_w \times [1 + \alpha(W - 12)], \text{kgf/m/cm}^2 $$

(5)

where $A_{12}$ – the impact viscosity of wood at 12% humidity; $\alpha (=0\,02)$ – an adjustment factor. The density $\rho_w$ was reduced to the standard value of $\rho_{12}$ by formula:

$$ \rho_{12} = \rho_w\{1 - [(1 - K)(W - 12)/100]\}, \text{kg/m}^3 $$

(6)

where $\rho_{12}$ – the density of wood at 12% humidity; $W = 8\%$; $K (=0\,5)$ – an adjustment factor

To compare the quality of wood formed after pruning in our study with the standard data, the quality coefficients as indicators relating to a unit of density were used. The property of wood offering the maximum acoustic radiation was evaluated by an indicator suggested by B.N. Ugolev [3]:

$$ K = \frac{E}{\rho^2}, \text{m}^4/(\text{kg} \times \text{sec.}) $$

(7)

where $K$ – a sound propagation constant; $E$ – the dynamic modulus of elasticity, N/m² or kg/m×sec²; $\rho$ – the density of wood, kg/m³.

The dynamic modulus of elasticity was calculated by formula:

$$ E = C^2\rho, \text{HPa} $$

(8)

$$ C = \frac{L}{T} $$

(9)

where $L$ – the sample’s length, m; $T$ – the sound lag, $10^6$ sec.

The sound lag was determined with the aid of the pulsing ultrasonic testing device UK-14 P (Spectehresurs, Russia).

3. Results and discussion

In frame of our study we have analyzed the wood formed as a result of 60 years’ growth after pruning conducted under the guidance of Prof. A.V. Davydov. It was reviled that such wood had high physical and mechanical properties. For example, the ultimate compressive strength along the grain of wood amounts to 51.6±1.02 MPa, with the standard value for spruce being 44.5 MPa [3]. The specific characteristic or the quality coefficient (0.96) is practically equal to the standard value (1.00). The impact viscosity is characterized by a much higher value (0.68±0.045 kgf/m/cm²) than the standard value of $A_{table}=0.40$. The specific characteristic (123.0×10⁻⁵) also exceeds the standard value ($K_{table}=90×10^{-5}$), which confirms the conclusion that this wood possesses a rather high quality.
In our study we also have revealed a high binding between the ultimate strength of wood ($\sigma$) and its density ($\rho$) which is assessed with the use of correlation ratio $R=0.73 \pm 0.140$. As result this binding can be described as: $\sigma = -17.663 + 0.131 \rho$.

In the context of impact viscosity ($A_{12}$), there is also observed a considerable relation to the wood density ($\rho$), which is confirmed by the correlation ratio $R=0.68 \pm 0.173$ and that relationship can be described as: $A_{12} = -1.444 + 0.004 \rho$.

As a result of the experiment where the minimally allowable quantity of upper live branch clusters was left (5 to 6 pieces) in the spruce cultures at the age of 23 years (the Gatchinskiy forest district, the Susaninskoye forest district), there was established the following. On a control plot, a permanent study area 2 (PSA), a decrease is observed in the wood density from the heartwood to the bark both in medium-sized trees and in large trees, with this decrease being more intensive in large trees due to an increased diameter growth. In the context of pruning (PSA 105), the picture is somewhat different. The medium-sized trees, prior to pruning, also reduced their density. After pruning, their density increased by 3.2%. The large trees, after pruning, showed an increase in their density by 15.6%. These differences are verifiable for the large trees and unessential for the medium-sized trees (with $P=0.95$). The difference in the large trees is due to a decrease in density down to 89.8% as compared to the prior-to-pruning period on the control plot, whereas, in the context of this experiment, the density increased by 5.4% as compared to the same period.

Based on results of this experiment, a method was developed for forming high-quality branchless wood of Norway spruce with an increased density and strength. The essence of the above method lies in selecting targeted trees at the age of 15 to 20 years. These targeted trees have a high growth class (Ia–II) and are going to join a mature forest stand. These trees must be straight and healthy, with their trunk being well shaped and with their crown being even and developed on all sides. These trees in the number of 600 to 800 per ha must be positioned uniformly with respect to the area and must not have large branches.

For purposes of producing high-grade timber as much as possible, the pruning process shall be carried out such that 5 to 6 upper live branch clusters be left on the tree. Next, on an annual basis, when one live branch cluster is growing, one live branch cluster from below must be removed as well. So this quantitative range of 5 to 6 upper live branch clusters is maintained for a long time, thus reducing an increment of trees in height and diameter, and lowering the content of young-growth wood. At the same time, the summer wood content remains to be at the level of control trees. As a consequence of this, the wood is formed with increased density and, respectively, increased strength, since there is a high correlation between these indicators.

As far as a season suitable for the green pruning is concerned, it is suggested that the most secure season in terms of disease-producing factors is the summer-autumnal period (July – October) and the spring time prior to the period of sap flow (late March - mid-May). The carrying out of this measure over the period of mid-May through the end of June is not allowed because, during an intensive sap flow, this leads to abundant sap- and resin-flow as well as to an effortless and frequent bark stripping at the risk of pathogenic infection. The winter pruning is prohibited for fear of wood dehydration through wounds. Branches and boughs can be removed all the year round. It is recommended that this silvicultural tending in spruce stands be carried out in combination with thinning (regulating the thickness by means of clean cuttings).

The study into experiments on pruning on permanent study areas, established by Prof. A.V. Davydov and continued by us, has shown that the wood formed as a result of 60 years growth has resonating characteristics (table 1). The average value of acoustic constant constitutes 11.4 m^4/kg×sec., whereas its optimal value for using this wood in instrument-making is equal to 12 m^4/kg×sec. and over [3]. However, a considerable body of samples displayed even a larger value of this constant.

The results of the study into radial cores of wood formed over the period of 24 years after the moderate pruning to large trees (the Gatchinskiy forest district) have shown that the sound propagation velocity against the grain constitutes $3.28 \times 10^{-6}$ sec./cm in experimental trees, and $3.89 \times 10^{-6}$ sec./cm in control trees. These are rather high indicators applicable to resonant wood. The difference in the sound
propagation velocity has turned out to be unessential with the five-percent level of significance. The width of an annual ring in control trees and experimental trees is the same and averages to 2 mm.

Thus, the pruning did not have an impact upon the above indicators, and yet it contributed to shaping a uniform branchless structure. However, due to the lack of self-pruning in control trees, it is practically impossible to produce resonant wood in the form of a mass composed of such trees.

Table 2. Resonating characteristics and related characteristics of spruce wood formed under the influence of pruning (Norway spruce, 120 years).

| Indicator                           | Average meaning for untreated stands [3] | Average meaning | ±δ   | V, % | P, % |
|-------------------------------------|------------------------------------------|-----------------|------|------|------|
| Density (kg/m³)                     | 360                                      | 543.5 ± 6.88    | 32.979 | 6.07 | 1.26 |
| Dynamic modulus of elasticity E, HPa| 16                                       | 20.8 ± 0.41     | 19.648 | 9.44 | 1.97 |
| Acoustic constant K, m⁴/(kg×sec.)   | No data                                  | 11.40 ± 0.120   | 0.577  | 5.06 | 1.05 |

One more result of this research - elaboration of method for forming resonant wood of Norway spruce. The summary of this method: by analogy with the above selection of trees for forming wood of increased density and strength, a selection is also made of stands and targeted trees (table 2). For purposes of the highest possible production of high-grade timber, the selected trees, with the use of a pole saw, go through pruning in 3 steps upward to 2 m, and then in 5 years upward to 4 m, and once more in 5 years upward to 6 m. Thus, by the age of 25 – 30 years, a 6 m-long branchless zone must be formed on the butt-log portion. Another version of this method is with pruning in 1 step upwards to 6 m at the age of 25-30 years though the resulting volume of high-grade timber will be lower. In this case, branches are removed in the compensation zone and the low-yield zone of the crown (2/5 to 1/2 in length). It is also possible to work on the medium-yield zone by leaving at least 1/3 of the live crown on the tree or 8 to 10 branch clusters. Once the mature forest stand has been felled, a completely branch-free mass of wood is cut out of these trees by a method of radial rough cutting, with which it is possible to produce resonant hewn blanks for making stringed and plucking musical instruments.

It is worth noting that the wood which, according to the final rejection (sizing), does not completely meet the necessary requirements may be used for other purposes, for example, for producing aviation-related and other special timber assortments. Apart from this, according to Prof. V.I. Fedyukov [11] who optimized cross-grained cutting options for resonant timber, "the lowest sort of an impersonal plank does not constitute a bar to producing resonant blanks if there is a careful individual pattern cutting".

Severe requirements applicable to resonant wood, its restricted range, and a low yield of material out of the block (no more than 5%) make this wood expensive and in very short supply. So there is a problem of regeneration. The cost per m³ of resonant coniferous blanks for string-plates of stringed and plucking musical instruments constitutes 100,000 RU in Russia and up to 150,000 USD abroad. Combining a moderately intensive pruning with a reasonable stand thickness makes it possible to purposefully grow a wood material possessing acoustic characteristics suitable for instrument-making. Apart from this, it is possible to form a wood material with improved physical and mechanical properties by regulating the crown length of targeted trees and maintaining 5 to 6 live branch clusters for a long time.

4. Conclusion
Studies have found that as a result of pruning, made by Prof. Davydov in 1929, for 60 years wood was formed with enhanced physical and mechanical properties. The compressive strength along the fibers is $51.6 \pm 1.02$ MPa, with a standard value of 44.5 MPa for Norway spruce. The quality factor (0.96), is almost equal to the standard (1.00). Impact toughness is characterized by a much larger value of $0.68 \pm 0.045$ kgf m/cm$^2$ than the standard ($A_{\text{stand}} = 0.40$). In addition, it is also revealed that the formed wood also has resonant properties. The average value of the acoustic constant is $11.4 \text{ m}^4/\text{kg} \times \text{sec}$. When removing living branches of high intensity (5-6 upper live branch clusters were left), led to a significant increase in the density of wood (by 15.6%) for trees with diameter larger than average in comparison with untreated stands.

By combining high-intensity and medium-intensity pruning of living branches with a rational density of the stand, it is possible to purposefully grow wood with enhanced physical and mechanical properties, as well as resonant wood for the manufacture of musical instruments. Due to the limited resources of resonant wood and the high cost, there is a need and possibility of its formation and cultivation.

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