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PIANO HAMMER TESTING DEVICE

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Abstract. The piano hammer testing device described here makes it possible to investigate the dynamical force-compression characteristics of piano hammer, and, using the hereditary (hysteretic) hammer model, to find the hammer parameters by numerical simulation of the dynamical experiments.

Key words: grand piano, piano hammers, hammer model, hammer-string interaction.

1. INTRODUCTION

According to the hammer models considered before the loading and unloading of the hammer are the same. The usual model of the hammer connects the force exerted by hammer F and the hammer felt compression u in the form of the power law [1–4]

$$F = F_0\, u^p \,. \tag{1}$$

Here F_0 is the hammer stiffness and p is the compliance nonlinearity exponent. Thus the features of the hammer are strongly determined by these two parameters, which may be easily measured in statical experiments. However, the dynamical features of piano hammers are significantly more complicated.

The results of the experiment provided by Yanagisawa, Nakamura and Aiko [5,6] show the significant influence of hysteresis, i.e. loading and unloading of the hammer are not alike. Furthermore, the force-compression relationships of the hammer are essentially nonlinear, and the slope of the dynamic force-compression curve is strongly dependent on the hammer velocity. The model of the hammer that takes into account all the dynamical features of the hammer and uses the real hammer parameters that are independent of the hammer velocity was derived in [7] in the form

$$F(u(t)) = F_0 \left[u^p(t) - \frac{\varepsilon}{\tau_0} \int_0^t u^p(\xi)\, exp \left(\frac{\xi - t}{\tau_0} \right) d\xi \right] . \qquad (2)$$

According to this model, the real piano hammer possesses history-dependent properties or, in other words, is made of the material with memory. Two additional hereditary parameters: hereditary amplitude ε and relaxation time τ_0 are involved to describe the hysteretic behaviour of the hammer. The constant coefficient F_0 is here the instantaneous hammer stiffness, and p is the compliance nonlinearity exponent.

Suitable values of elastic parameters F_0, p and hereditary constants ε, τ_0 for various hammers may be obtained by numerical simulation of the dynamical experiments. The mathematical model of this experiment presented below can be described by equation

$$m\frac{d^2u}{dt^2} + F(u) = 0, \qquad (3)$$

with the initial conditions

$$u(0) = 0, \;\; \frac{du}{dt}(0) = V_0. \qquad (4)$$

Here m and V_0 are the hammer mass and the hammer velocity, and $F(u)$ is defined by Eq. (2).

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement shown in Fig. 1 gives a possibility to obtain the dynamical force-compression characteristics of piano hammers and, using the hereditary model of the hammer (Eq. (2)), to find the hammer parameters by numerical simulation of the dynamical experiments.

In these measurements the hammer struck the piece of the string, fixed on the force sensor. The device consists of two main parts. The first mechanical part gives the needed velocity of interaction of the hammer with the string. The second part includes the force and the gap sensors with the respective electronics for the force-time and compression-time dependencies registration during the strike.

General view of the device is shown in Fig. 2. A piezoelectric wide-band ceramic plate is used as a force sensor. To measure the hammer compression, an infrared optical system has been developed. During the strike, the flag placed on the end of the shank changes the intensity of the infrared light between the emitter and receiver diodes that gives the possibility to measure the hammer felt compression. To avoid the influence of the shank deformation, it is made of rigid titanium tube.

The mass of the shank is equal to $M_s = 13.5$ g, and the mass of the hammer holder unit is equal to $M_u = 33$ g. Thus the effective mass that is added to the hammer mass during the numerical simulation of the experiment is equal to $M_a = 1/3\ M_s + M_u = 37.5$ g.

The analogue signals from the force and the gap sensors are converted into two sets of data by a digital signal processor ADSP-2181. This 8 channel, 12 bit signal processor allows:
- to set up the data communication speed from device sensors to computer,
- to present data in a scope mode or in an analyser (FFT) mode,
- to save data in a file,
- to print oscillograms and spectrograms.

The device is controlled by a personal computer via a RS232 cable.

3. SENSOR CALIBRATION

The force sensor was calibrated by dropping different roller bearings onto the force sensor. To avoid the roller bearing jumping up after the strike, the piece of thin sticky tape was glued on the force sensor.

The integration over the time of the registered electrical signal gives the value of the roller bearing pulse P_0 in units (V s). The roller bearing mass and the altitude of dropping are known values, therefore the value of the acting pulse M_0 in units (kg m/s) is also known. Thus the force calibration coefficient K_f can be found from the equation

$$K_f P_0 = M_0 = m_0 V_0 = m_0 \sqrt{2gH_0}. \tag{5}$$

Here the m_0, V_0, and H_0 are the roller bearing mass, its velocity, and the amplitude of falling and g is the gravity constant. The value of the calibration coefficient was found by averaging of the results of the series measurements, and it is equal to $K_f = M_0/P_0$ =18.3 N/V.

The compression sensor has two different outputs. The first output is a direct current output DC, and my be used for static measurements. The second one is an alternating current output AC, that is more sensitive, and it is used for dynamical measurements.

The calibration of the gap sensor was provided by registration of the AC and DC signals when the shank falls freely down. This time dependence of the AC channel output is shown in Fig. 3. The time dependence of the DC channel output is similar.

In Fig. 4 is displayed the dependence of DC versus AC channel output. This linear dependence indicates that in spite of the different schematic formation of the channels they are functioning identically. Thus we may be sure that the AC channel has a wide-band amplifier enough to reproduce the form of the signal.

The linear dependence shown in Fig. 4 may be approximated as

$$U_{dc} = 4.473 + 0.1005\, U_{ac}. \tag{6}$$

This function relates the output voltage of DC and AC channels.

From Fig. 3 we find that the optical aperture is slightly close if the output voltage in AC channel exceeds $U_{ac} = 0.0815$ V. If the output voltage in AC channel exceeds $U_{ac} = 4.710$ V, then the optical aperture is closed. The diameter of the working aperture, or the maximum value of hammer felt compression was found by using the micrometer. It is equal to $D_a = 2.0$ mm.

During the falling down through such a small distance the force of gravity changes the shank velocity V_a just a little. Therefore, we may assume that during the measurement the velocity V_a is a constant value. In this case it is equal to

$$V_a = D_a/t_a = 1.52\, m/s\,, \tag{7}$$

where $t_a = 1.316$ ms is a flying time obtained from Fig. 3.

Because the displacement of the flag through the optical aperture is proportional to time, using Eq. (7) we may change the time axis in Fig. 3 by displacement axis (hammer compression) . This calibration curve is presented in Fig. 5. For the numerical calculations this experimental curve may be approximated by a polynomial

$$u = \sum_{i=0}^{7} a_i\, U_{ac}^i\,, \tag{8}$$

where u, mm – hammer felt compression, U_{ac}, V – output voltage, and the coefficients a_i are equal to:
$a_0 = -0.13324$; $a_1 = 2.28318$; $a_2 = -3.45546$; $a_3 = 3.15284$;
$a_4 = -1.60758$; $a_5 = 0.456363$; $a_6 = -0.067288$; $a_7 = 0.0040158$.
Similar dependence for DC channel output can be written using Eq. (6).

4. HAMMER TESTING

To demonstrate the capabilities of the device, two types of experiments were made. The first experiment is performed to estimate the reliability of the hysteretic model. According to this model the form and the slope of the force–compression characteristics depend on the hammer velocity. In this measurement the hammer (*Renner* A1) struck the piece of string of diameter $d = 4.3$ mm fixed on the force sensor, and the force – compression relationships for the various hammer velocities were obtained.

The comparison of the theoretical model with the experimental data is presented in Fig. 6. Experiment confirms the theory fairly well. The slope of the force – compression characteristics increases with the growth of the hammer velocity. On the other hand, the hysteretic theory makes predictions in good agreement with experimental data for various hammer velocities. All three experimental curves are described by the theory with the same constant values of the hammer parameters:
$F_0 = 400$ N/mm^p, $p = 2.4$, $\varepsilon = 0.51$, $\tau_0 = 400$ μs.

The second set of measurements was performed to clarify whether the hammer parameters depend on the diameter of the striking string. For this purpose in the experiments the hammer (*Abel* A1) struck different strings and the flat surface of the force sensor with a constant velocity $V_0 = 0.7$ m/s.

The experimental data and the numerically simulated curves are presented in Fig. 7. The hereditary parameters for all the four curves are the same: $\varepsilon = 0.69$ and $\tau_0 = 250$ μs. The elastic parameters of the hammer are varying with the change of the string diameter.
In case when the hammer struck the flat surface, we have the values of the elastic parameters: $F_0 = 480$ N/mm^p; $p = 2.7$.
When the hammer struck the string, the next triple sets of parameters were obtained:
if $d = 4.3$ mm, then $F_0 = 400$ N/mm^p; $p = 2.3$;
if $d = 2.25$ mm, then $F_0 = 330$ N/mm^p; $p = 2.0$;
and if $d = 1.25$ mm, then $F_0 = 270$ N/mm^p; $p = 1.8$.
Thus, we may state that the hammer parameters strongly depend on the string diameter, or on the conditions of interaction.

5. CONCLUSION

To measure the nonlinear elastic and hereditary parameters of the piano hammer a special device has been developed. This experimental arrangement gives a possibility to investigate the dynamical force-compression characteristics of piano hammer, and, using the hereditary (hysteretic) hammer model [7], to find the hammer parameters by numerical simulation of the dynamical experiments.

It has been shown that physical assumptions about the history-dependent properties of the hammer felt are confirmed by the experiments. The hereditary (hysteretic) model of hammer with memory describes the behaviour of such microstructured material as a hammer felt rather well. We may really see the dependence of the slope of the force – compression characteristics of the hammer on the rate of loading (Fig. 6).

The model demonstrated here makes predictions in good agreement with experimental data for various types of piano hammers and for a broad range of hammer velocities. This model makes it possibile to find the additional intrinsic (hereditary) parameters of the hammer.

It has been shown that the values of the hammer parameters depend on the diameter of the struck string (Fig. 7). For this reason we must indicate the diameter of the striking string, then we tell about the hammer parameters.

The piano hammer testing device in conjunction with the hysteretic model of the hammer is a powerful instrument for matching of the piano hammers, as well as for their manufacturing. The numerical simulation using the hysteretic hammer model may significantly simplify the process of manufacturing of the piano hammers.

By use of this device it is possible to find the dependencies of the hammer parameters on the technological conditions of manufacturing. Therefore the knowledge of these dependencies gives a good practical hint to choose a better technological process for the hammers manufacturing. In this sense, the hysteretic hammer model is an irreplaceable model.

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FIGURE CAPTIONS

Fig. 1. Experimental arrangement required for dynamical testing of piano hammers.

Fig. 2. Piano hammer testing device.

Fig. 3. Time dependence of the AC channel output.

Fig. 4. Dependence of DC versus AC channel output.

Fig. 5. Calibration curve.

Fig. 6. Force-compression characteristics of the *Renner* $A1$ hammer for the various initial hammer velocities. Circles, squares, and triangles denote the experimental data points. The solid lines are the calculated curves.

Fig. 7. Force-compression characteristics of the *Abel* $A1$ hammer striking the various strings and the flat surface. Circles, squares, triangles, and asterisks denote the experimental data points. The solid lines are the calculated curves.

KLAVERI HAAMRITE KATSETAMISE SEADE

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On kirjeldatud seade, mille abil saab uurida haamri töö füüsikalisi protsesse. Haamri hüstereesilisel mudelil põhinev seade ja selle tarkvara võimaldavad modelleerida helitekkeprotsessi ja ennustada klaveri kvaliteet.