Double basses on the stage floor: Tuning fork–tabletop effect, or not?

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The question whether or not double basses can benefit from a compliant and radiating stage floor in the low end of their tonal register, similar to the well-known tuning fork–tabletop effect, was examined through field experiments in five concert halls. The topic comprises several aspects: (1) How well the mechanical impedances of double basses and the stage floor match, (2) amount of vibration velocity transmitted to the floor through the end pin of the bass, and (3) radiation efficiency of point-excited bending waves in the stage floor far below the coincidence frequency. Each aspect represents a prerequisite for the tuning fork–tabletop effect to take place. The input impedance at the end pin was measured for three representative double basses. The stage floors of five orchestra halls were measured with respect input impedance and damping, while sound radiation to the audience area was measured for two of them. In Lindeman Hall, Oslo, all conditions for the tuning fork–tabletop effect to take place were clearly met. The contribution from the stage-floor radiation to the sound pressure level in the audience area was found to be about 5 dB between 40 and 60 Hz, and even higher between 30 and 40 Hz. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3651791]

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I. INTRODUCTION

It is well known that string instruments, due to their limited sizes, are not radiating much below their Helmholtz frequency, which for double basses normally will be found right above 60 Hz.[1] Still, modern double basses play tones down to one octave below that (B0 at 30.9 Hz, wavelength in air, 11 m; four-string bass without extension: E1 at 41.2 Hz, wavelength in air, 8.3 m). In this low register, the size of the bass corpus is by all measures small compared to the wavelength of the fundamental and lower partials. If such low frequencies shall be clearly perceived by the audience, an additional source of radiation complementary to the instrument's corpus would be highly beneficial. According to professional bass players' experiences, the stage floor may contribute significantly to the low-frequency sound. The hypothesized explanation has been that the floor radiates in part by radiating the vibration energy transmitted to the floor via the end pin (tuning fork–tabletop effect). Concert halls differ largely with respect to this desired property. One reason is that the necessary conditions for an efficient tuning fork–tabletop effect to occur have not yet been clarified despite a number of studies starting way back in the 1930s.

Neues Gewandhaus in Leipzig (destroyed in World War II) was famous for the powerful sound of the cello and double-bass sections,[2] an effect that was attributed to vibrations transmitted from the stage to the wooden main floor. The vibration transmission was thought to be particularly efficient as the entire stage rested on this floor. However, acoustical measurements in the hall at that time gave only weak support for this theory.[3,4] A similar effect is reported for Concertgebouw in Amsterdam "where in the front half of the main floor the double basses cause the seats to vibrate when they play fortissimo. These vibrations are pleasant and may contribute in some way to the fine reputation of the hall."[5]

Advice on the design of the stage area in modern time, based on redesign of a less successful concert hall, includes the use of a wooden stage floor "as thin as other considerations permit."[6] As today's building codes in many cases exclude lightweight floors due to safety considerations, new concert halls have often been designed with rather robust stage floors.

Experience shows that stage risers can have acoustical advantages for the bass sound when used on heavily constructed stage floors.[7] Using risers of moderate size ($1\ \text{m} \times 2\ \text{m}$), Askenfelt[7] found that the average sound pressure level in the audience area (far field) increased by 3 dB in the range 40–60 Hz compared to a very rigid stage floor. Beranek *et al.*[6] reported a gain of as much as 6 dB of the fundamental when basses were played on risers compared to a concrete floor. Further acoustical aspects on risers and stage floors, including theoretical models and numerical simulations, have been reported rather recently.[8,9]

The size and effect of risers is, however, always limited and this approach is probably not the ultimate solution for a deep, well-defined bass sound in a concert hall.

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Preferably the stage floor itself should provide the acoustical support. This study investigates the conditions for such an acoustical effect of the stage floor to occur. The measurements include the whole chain from transmission of vibrations from the double-bass bridge to the stage floor followed by the radiation from the floor into the audience area. The coupling between the bass and the floor is studied through impedance measurements.

Five stage floors that differ greatly in design and properties were included in the study: Oslo Concert Hall [(OCH), opened 1977], Berwald Concert Hall of the Swedish Radio Company, Stockholm [(BwH), 1979], The Lindeman Hall of Norwegian Academy of Music, Oslo [(LiH), 1988], The Norwegian Opera and Ballet rehearsal hall, Oslo [(NORH), 2008], and The Norwegian Opera and Ballet orchestra pit [(NOOP), 2008].

A case study of a hall with a clear and recognized effect of the stage floor on the bass sound, the LiH, is presented first, followed by a theoretical background. Measurements of key parameters, including impedances, damping, and radiation are reported.

II. RADIATION FROM THE STAGE FLOOR: A CASE STUDY OF A HALL WITH DESIRED PROPERTIES

The hall with the most promising qualities with respect to energy transfer and radiation was LiH, which seats up to 430 people in the audience section, and provides a very satisfying sound from the double basses—deep, but still transparent, and well balanced. It is a relatively small hall with a volume of $\sim 4140\ \mathrm{m}^3$, and reverberation times 1.9, 2.2, 2.1, and 1.8 s for the octave bands 63, 125, 250, and 500 Hz, respectively. No estimation of the 31 Hz band was available. The stage floor is made of 22 mm hardwood parquet (Merbau, *Intsia bijuga*/*Intsia palembanica*, density of a sample 870 $\mathrm{kg/m^3}$) resting on low joists only 30 cm apart. The joists are "cushioned" on 5–10 mm thick blocks of rubber, which rest on large floating, reinforced concrete blocks (see Fig. 1). All cavities around the floating elements are filled with rock wool.

The stage area is 170 $\mathrm{m^2}$ with joists oriented from rear to front of the stage, and the parquet crossing. When walking on the stage, the floor construction is perceived as "dead." No resonant ringing could be perceived when tapping the floor, only a well-damped thump.

A. First experiment: Vibration amplitude distribution in the floor

1. Method

In the first experiment we measured how the vibration amplitude faded out around the point of excitation, i.e., which region of the floor was truly active. The floor was excited by a shaker[10] in the region where the double basses are positioned, hanging in rubber bands and connected to the floor via a thin rod (stinger). A reference accelerometer was positioned adjacent to the excitation point, while a second accelerometer was placed successively at ten positions from 5 to 300 cm from the excitation point (5, 10, 15, 20, 30, 40, 75, 125, 200, and 300 cm)—and in two directions: sideways in the direction towards the stage center, and forward in the direction towards the audience. Sweeps from 20 to 500 Hz were run in sequences of 30 s. The signals of the two accelerometers were recorded at a sampling rate of 22 050 Hz. The damping in the floor was measured using hammer blows and recording the amplitude decay (−35 dB) with an accelerometer close to the striking point. Both for sweeps and hammer blows two series were measured—on and midway between joists.

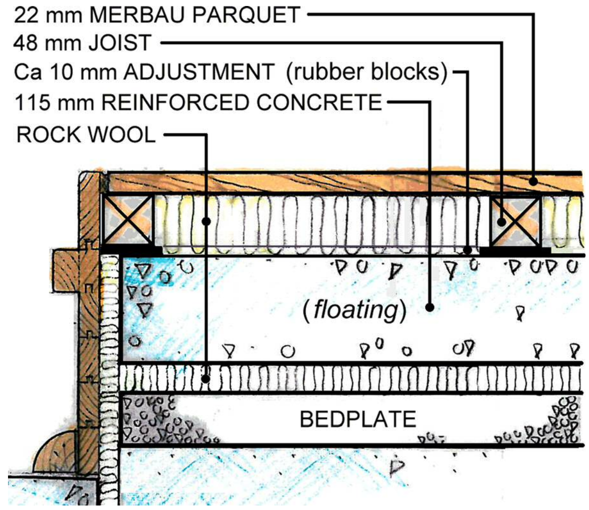

FIG. 1. (Color online) Stage-floor construction in LiH. The joists, only 30 cm apart, are resting on floating, reinforced concrete, with thin rubber blocks in between. (Drawing made available by courtesy of Arkitektgruppen Lille Frøen AS.)

2. Results

The vibration amplitude distributions for the point-driven floor are shown in Figs. 2(a)–2(d) for four 1/3-octave bands ranging from 25 to 200 Hz. Figure 2 shows isodynamic lines (−3, −6, −10, −15 dB) in terms of ellipses interpolated through the formulas $x = L_X \cos\varphi$, and $y = L_Y \sin\varphi$ $(0 \leq \varphi \leq 2\pi)$, where L_X and L_Y are measured, isodynamic distances from the origin in the two directions indicated. As can be seen, the −6 and −10 dB isodynamic lines are found rather close to the excitation point (the distance being ≤50 and ≤80 cm in the two directions, respectively) in all cases between 25 and 200 Hz. The loss factor was quite high (between 0.3 and 0.6) below 80 Hz for the pliant sections, and even higher on the joists. (For more details, see Table II.)

The vibration patterns show a general change from fairly circular up to about 80 Hz, followed by a development into ovals stretched in the direction of the joists. At 200 Hz the stretching of the isodynamic lines has become quite pronounced [see Fig. 2(d)], a characteristic that remained for the higher frequencies measured. Half wavelengths of the bending waves in the floor along $(\lambda_{By}/2)$ and across $(\lambda_{Bx}/2)$ the joists are included in the the plots of Fig. 2 for comparison, covering a total range of 1.7–0.5 m approximately. The calculation of wavelengths is based on phase differences between the signals of the two accelerometers. These values proved a little noisy, so in order to get a fair estimate, phase

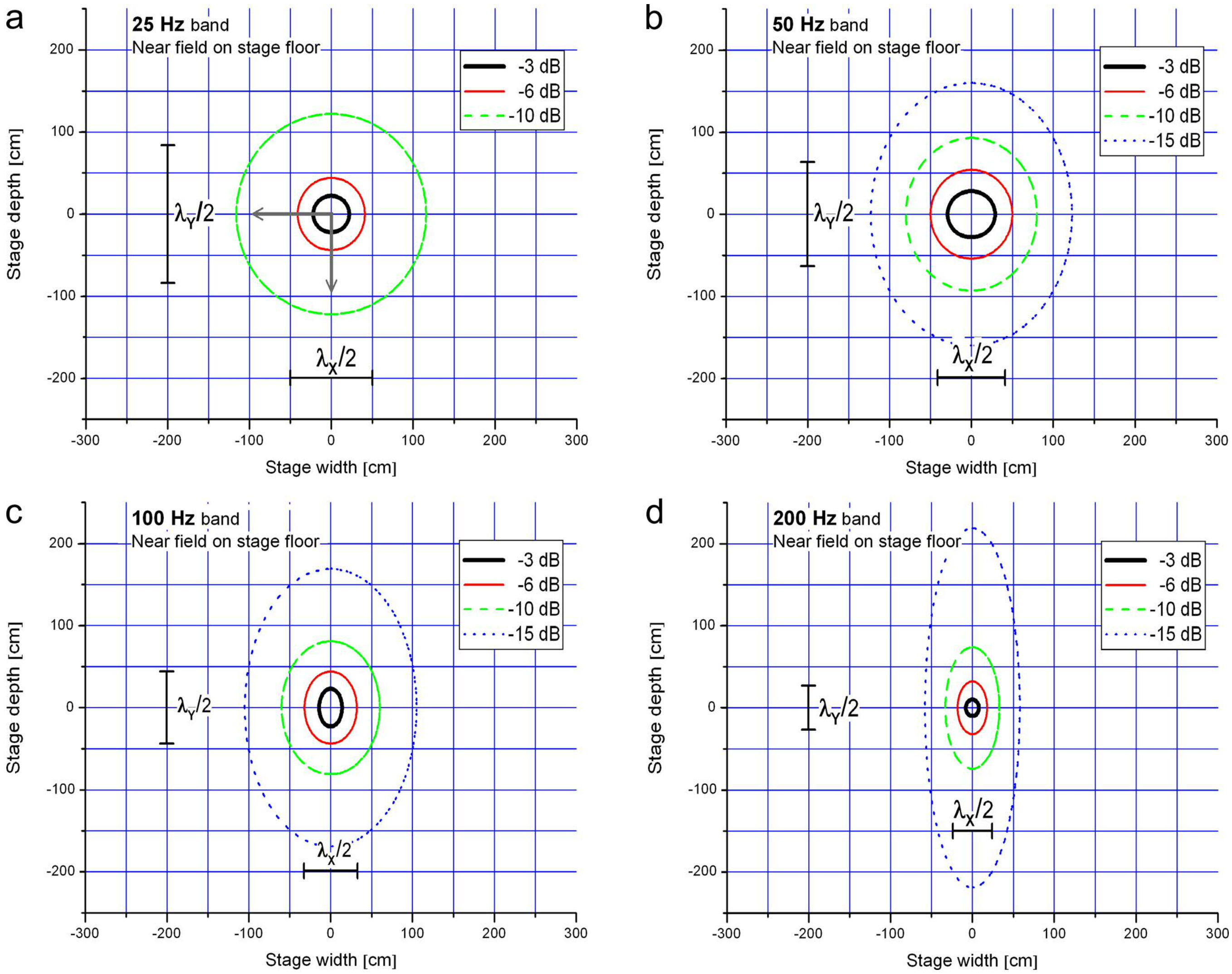

FIG. 2. (Color online) Distribution of vibration velocity amplitudes in LiH stage floor during sinus sweep measured at ten distances from the point of excitation (5, 10, 15, 20, 30, 40, 75, 125, 200, and 300 cm), and in two orthogonal directions [stage width and depth, as indicated by arrows in (a)]. Excitation was between joists. (a)–(d) Four selected frequencies (25, 50, 100, and 200 Hz) with interpolated circles/ellipses indicating isodynamic lines (−3, −6, −10, −15 dB). These are fairly circular below 80 Hz. Measured half bending wavelengths are included.

differences of frequencies in the entire third-octave band were included in a series of least-squares error calculations. In general, the measured bending wavelengths along the joists are slightly longer than those crossing. The classical estimate of the bending wavelength in an infinite, isotropic plate ends up with wavelengths between the two series actually measured. The rule of thumb for wooden plates, derivable from Cremer and Heckl,[11] reads as follows:

$$\lambda = \sqrt{\frac{1.8\, c_L h}{f}}, \qquad (1)$$

where λ is longitudinal propagation speed, h is plate thickness, and f is frequency.

When inserting $c_L = 4\,990$ m/s in Eq. (1)—which was the measured[12] speed in the length direction of a parquet sample—we get the rule of thumb values shown in Fig. 3, with a coincidence frequency of 585 Hz. This is a decade over the frequency range of interest, i.e., <60 Hz. (Across grains, c_L gives an isotropic coincident frequency of 1940 Hz.)

In most bands, the estimated half wavelengths fall somewhere between the isodynamic lines for −6 and −10 dB. These values are interesting as the predicted diameter of the effective radiating area is close to half a wavelength (see Sec. III).

B. Second experiment: Sound pressure vs floor vibration

1. Method

In a second experiment, the sound pressure in the audience area vs vibration velocity of the stage floor in the area where the double basses normally are positioned was measured. A three-channel setup was used—a force transducer attached between the stinger from the shaker and the floor (permitting supplementary calculations of power), an accelerometer mounted on the stage floor adjacent to the force transducer, and a calibrated studio microphone (omnidirectional, BK 4007). This time, the floor was excited in two series 15 cm apart (*between* and *on* the

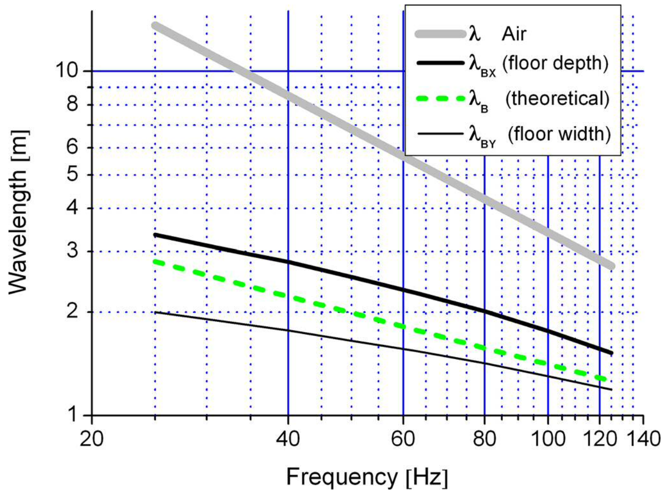

FIG. 3. (Color online) Measured bending wavelengths of the LiH floor in two directions, compared to wavelengths in the air (thick line) and to the rule of thumb, Eq. (1) (dashed line).

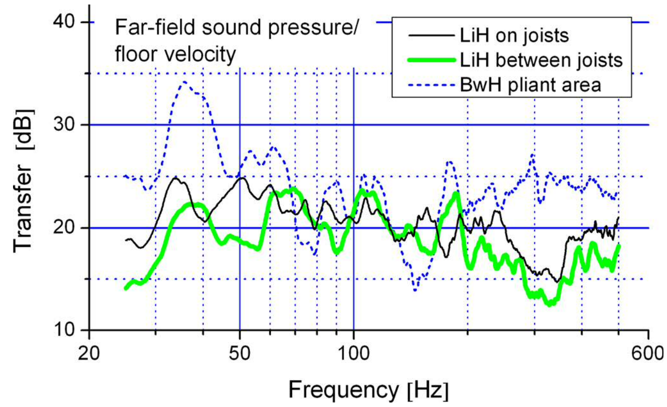

FIG. 4. (Color online) Transfer functions from stage floor to sound in the hall for LiH and BwH calculated as sound pressure/stage-floor velocity averaged over six positions in the audience area (LiH on joists, thin line; LiH between joists, thick line; BwH in pliant area, dashed line). Sound pressure is relative to 94 dB SPL, while other parameters are relative to ISO standard units.

joists). The microphone was placed at distances 170 cm above, and 8, 13, and 19 m away from the points of excitation, respectively. The first position was representing the near field as experienced by a (double bass) player, the latter three were representing normal head positions of listeners seated at three different rows. In each row, two different seat positions were used, about 3 m apart. This makes $1 + 3 \times 2$ microphone positions and two shaker positions, with a grand total of 14 cases. Each case was recorded twice and averaged. For each microphone position, 4 s of silence was recorded, from which the background noise of the ventilation system, etc., could be estimated.

2. Results

The measurements permitted the calculation of transfer functions between sound pressure at different seats in the audience area and the stage-floor velocity at the excitation point.

In the far field (8 m and more), the measurements at two seat positions in each row were averaged to minimize the effect of potential node-line dropouts caused by standing waves. The signal-to-noise (S/N) ratio did not influence the measurements in the range of main interest (typical S/N ratio 20 dB, worst case about 6 dB above 30 Hz). The obtained averaged transfer functions when the floor is excited on and between joists, respectively, are shown in Fig. 4. In the same plot a corresponding curve from BwH is added for comparison.

The plots show clear evidence of effective radiation down to quite low frequencies for both halls. All transfer functions show low-frequency roll off starting just above 30 Hz. Apart from that, the transfer functions of LiH have very little slope in the displayed frequency range. In the case of BwH, the transfer curve even displays a quite noticeable increase at lower frequencies. The transfer functions in the near field were measured to be some 5–15 dB higher, but without any particular spectral colorization.

When running the sweeps (power input to floor ~1 mW), the sound was audible from above 35 Hz approximately, although not continuously through all frequencies until, say, above 80 Hz (see sound-pressure dips in Fig. 4). A significant rise in perceived level took place around 120 Hz, which still is about five times below the estimated critical frequency. In summary, the initial case study of the LiH showed that the bass players' preference for the hall is supported by the measurements. A contribution to the sound in the hall from the vibrating stage floor would be possible down to about 30 Hz.

After some theoretical considerations in the following, the conditions for a significant transfer of vibrations to the stage floor via the end pin of the double bass are treated.

III. THEORETICAL CONSIDERATIONS

While double-bass players unanimously claim the importance of a compliant floor for projecting low-range tones, acousticians seem more reserved in this matter. Concerns are sometimes expressed that the floor acts as an absorber for frequencies much lower than the critical frequency. It is true that an infinite plate without losses will not radiate at all below the critical frequency when saturated. With damping, the radiation may, however, be substantial also for plane waves on an infinite plate (see Fig. 5, where η is the loss factor—based on equations from Bodén *et al.*[13]).

The current case with a double bass on the stage floor is well approximated by a point-excited infinite plate. When the floor is thin, the bending wavelength is small and the vibration amplitude decreases rapidly with distance from the excitation point. As seen in Fig. 2, the vibration level has decreased -10 dB within half a wavelength from the shaker. The amplitude decrease is augmented in LiH with a loss factor of about 0.3–0.6 below 60 Hz, but high damping is not a necessary condition as such for the approximated case.

For a point-excited infinite plate, a net radiation, equivalent to that of a baffled piston with radius a of approximately a quarter of the floor's bending wavelength and vibrating with the velocity of the excitation point, will result,[11,14]

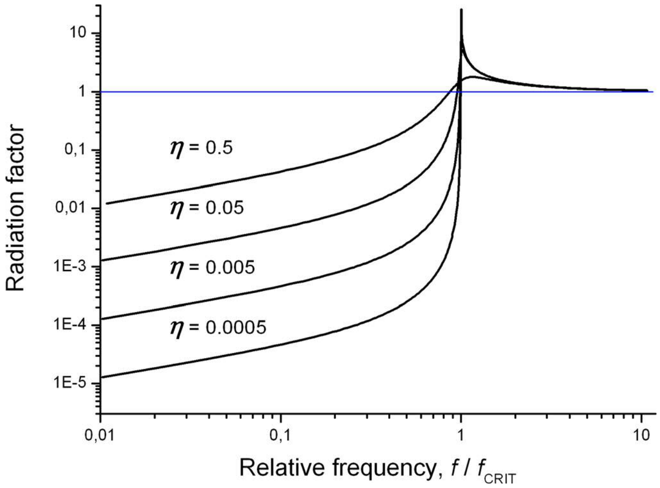

FIG. 5. (Color online) Radiation factors of an infinite plate with losses (indicated by loss factor η, see the text). Adapted from Ref. 13.

$$a = \sqrt{\frac{2}{\pi^3}}\lambda_B = 0.254\lambda_B \approx \frac{\lambda_B}{4}, \tag{2}$$

where λ_B is the bending wavelength of the plate.

Intuitively this result is plausible. The wave fronts are circular and adjacent positive and negative quarter wavelengths will cancel each other and only half the central zone at the excitation point with radius of a quarter wavelength will be left over. The equivalent piston diameters in the two directions on the floor ($\lambda_{Bx}/2$ width, and $\lambda_{By}/2$ depth) are included in Fig. 2. The measured wavelengths in the direction along the joists λ_{Bx} are between 30% and 70% longer than crosswise for the frequencies in question.

The piston diameters are much wider than the spacing between joists, extending over five joists at the lowest frequencies (20–30 Hz), over two joists at 100 Hz, and over more than one at 200 Hz. The measured vibration areas (isodynamic lines) are approximately circular up to about 80 Hz, indicating small influence of the periodic structure. Above that range the vibration areas are successively stretched in the direction of the joists, and the strongly vibrating parts (-3 dB) are confined to the areas between joists. The wavelength in air is about a factor of 10 longer than radius of the piston below 80 Hz and the radiation from the piston areas can be considered equal in all directions.

The joists complicate the prediction of the driving point impedance compared to an infinite homogeneous plate. The stage floor in LiH can be modeled as a rib-stiffened periodic structure. For such structures there is a significant variation in driving point impedance with the position of the driver relative to the ribs.[15,16] The reported results apply to isotropic as well as orthotropic floor sheathing, such as wood. If the driver is located more than a quarter wavelength from the ribs, the structure behaves like an infinite plate, which defines the lower bound of the driving impedance. This condition is not at all met in LiH below 100 Hz (joist spacing 30 cm). For the limiting case with the shaker midway between joists in LiH, the impedance is more than 10 dB higher than infinite-plate condition in this range. When the driving point is on top of a joist the connection between the sheathing and joist (screws, glue) is highly influential. On, or close to, the joists the input mobilities are mainly dominated by the beam flexural stiffness.

IV. PROPERTIES OF THE DOUBLE BASS

A. Measurements of end pin impedance

Impedances of three medium- to high-quality double basses were measured—one small (3/4 size), student instrument (Wilfer 1969, Erlangen, Germany; string length 104 cm, mass 10.3 kg) and one large four-stringed (unknown maker, semi-professional use, 19th century, string length 108 cm, mass 9.5 kg), and one large five-stringed bass (professional use, Pöllman 1970, Mittenwald, Germany; string length 111 cm, mass 11.1 kg). Primarily, the impedance at the end pin was the subject of our interest.

These measurements were done with the instruments laid down on thick blocks of soft foam rubber. The end pin, pulled out some 5–6 cm, was hit by an impact hammer (BK 8202) on a specially designed adapter, to which an accelerometer (BK 4393) was glued (see Fig. 6, upper panel). The impedance was calculated (averaged over about 16 hammer blows) as $z(\omega) = j\omega F(\omega)/a(\omega)$, where F, a, and ω denote force, acceleration, and angular frequency, respectively. (This method was used for all impedance measurements in this paper.) In order to estimate the effect of a bass tilted 60° with respect to the stage floor—a common instrument angle when the player is sitting—an adapter with a 30° facing was excited in the same manner (Fig. 6, lower panel). The impedance difference due to the excitation angle was negligible in the range below 100 Hz, although significant differences could be observed for higher frequencies.

Figure 7 shows the impedances at the end pin when hit at 0° angle. The impedance curves are seen to be fairly similar up to about 100 Hz, within which range the double bass primarily acts as a mass. A linearized average of the three basses' impedances can be used as a generic description of the end pin impedances in the frequency range of greatest interest: The magnitude increases on average 4.3 dB/octave (compared to 3 dB for a pure mass)—from 1000 kg/s at 20 Hz to 10 000 kg/s at 100 Hz—while the phase remains near 90° throughout this range. (We will return to this simplification in Sec. V.) In the region from 100–200 to about 500 Hz, the three basses show phases closer to $-90°$ (i.e., springlike).

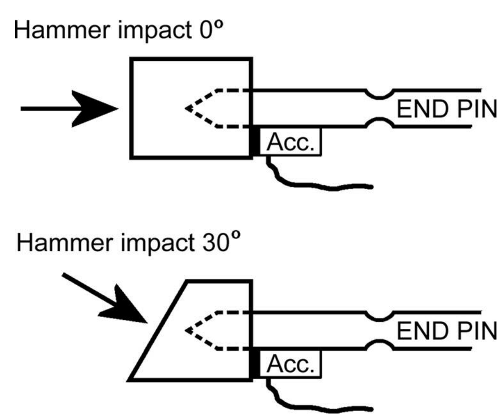

FIG. 6. Adapters mounted to the double-bass end pins facilitating clean force-hammer impacts at two angles (0° and 30°).

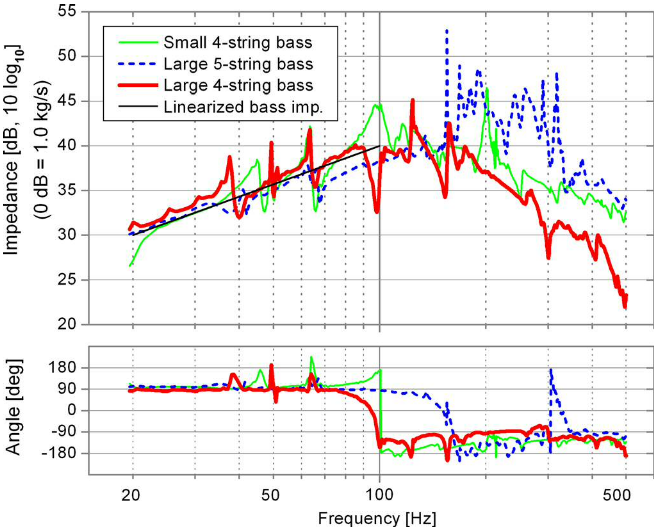

FIG. 7. (Color online) Input impedances measured at the end pin of three double basses. All basses show phase values of approximately 90° in the region 20–80 Hz. In the same interval the average impedance is rising approximately 4 dB/octave. Small four-string bass (thin line), large four-string bass (thick line), and large five-string bass (dashed line). The thin straight line indicates a linearized average.

In order to estimate the vibration (velocity) transfer from the bass to the floor we may use

$$H(\omega) = \frac{v(\omega)_{FLOOR}}{v(\omega)_{BASS\_CORPUS}} = \frac{z(\omega)_{END\_PIN}}{z(\omega)_{END\_PIN} + z(\omega)_{FLOOR}}. \quad (3)$$

Here, $v_{\mathrm{BASS\_CORPUS}}$ should be understood as the velocity of the end pin, when free, while v_{FLOOR} describes the end pin/floor velocity when these two bodies are coupled. The bass is thus considered as a velocity source with internal impedance z_{END_PIN} and short-circuit velocity v_{BASS_CORPUS}.

B. Power transmission

In an early preliminary experiment the transfer of vibration velocity from the bridge to the floor was measured in order to get a picture of a typical relation between the excitation of the bass at the bridge and the floor, respectively. Two accelerometers were used, one on the shoulder of the bridge at the low E-string, in plane with the bow (BK 4393), and one on the floor next to the end pin (BK 4375). The large five-string bass was played in BwH on a compliant section of the stage floor (see Sec. V for details on floor properties). Figure 8 shows the obtained transfer function of velocity from *bridge* to floor. [Observe that this transfer is not related to Eq. (3), which refers to the transfer of *end pin* velocity to the floor.] It is surprising to observe that the floor moves considerably more than the bridge at many frequencies in the range 20–40 Hz.

Later, when the bass and floor impedances had been measured, we calculated the power transfer to the floor based on playing of scales with loud, sustained tones (∼2 s) in the lowest two octaves (see Table I). In this way, we could estimate how much energy a double bass would be delivering to the floor during performance. In the bands 31–100 Hz the transmitted power ranged from 3 to 6 mW, approximately.

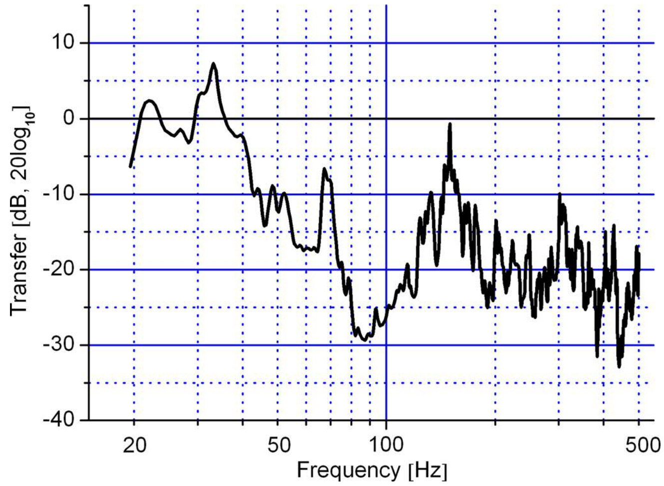

FIG. 8. (Color online) Vibration velocity transfer from the double-bass bridge to the floor adjacent to the end pin (five-string bass in pliant area of BwH).

However, these values do not constitute an upper limit for the power input to the floor. Had the bass been played with shorter tones, considerably higher amplitudes could have been obtained. From Table I we notice that the relative power transmission bridge to floor increases with descending frequency, reaching a maximum of 40% at 31 Hz. (In practice, input power was here calculated as $P(\omega) = \mathrm{Re}[z(\omega)]a(\omega)a^*(\omega)/\omega^2$, where the asterisk (*) denotes conjugated—for the bridge and the floor alike. Relative power transmission thus becomes $P(\omega)_{\mathrm{FLOOR}}/P(\omega)_{\mathrm{BRIDGE}}$.)

As a comparison with the power values in playing, the input power to the stage floor during the sweep for measuring transfer functions in the hall was around 1.0 mW. As mentioned, this sinusoidal excitation gave a clearly audible sound in LiH down to the lowest frequencies (35 Hz).

C. Playability

Quite another aspect of the supporting floor is the *playability* of the instrument when standing on different types of foundation. Every bass player knows that the feel of the instrument varies vastly with the properties of the floor. The experiences from the BwH are striking in this respect. BwH was designed with the philosophy that, in order to avoid low-frequency noise due to heavy TV cameras during broadcasted concerts (the hall was designed in the early 1970s),

TABLE I. Power transmission between the five-string bass and the BwH pliant floor (values are rounded). Calculations are based on realistic playing in *f*–*ff*.

1/3-octave bands, mid. frequency (Hz)	Power input at bridge (mW)	Transmission to floor (mW)	Percent of power transmitted (%)
20	1	0.4	36
25	7	1.6	21
31	12	4.9	40
40	49	4.9	10
50	111	2.9	3
63	219	5.6	3
80	299	3.0	1
100	329	4.1	1

the entire stage floor should be as rigid as possible. The concept resulted in a floor where the parquet was glued with asphalt directly on a concrete foundation resting on bedrock. This design proved to be most uncomfortable for the musicians (not only the bass players), so after some years (in 1995) it was decided to replace most of the floor with stage lifts, which included a cavity under the covering parquet.

The bridge *mobility* of a large five-string double bass was measured in the LiH under three conditions: (a) Standing on the stage floor, on and between joists (b) standing on the solid bedplate below the floor through a hole in the parquet (see Fig. 1), and (c) suspended in the air. The resulting mobility ratios are shown in Fig. 9. The highest mobility is clearly found when the bass is standing on the compliant floor (but similar features are seen also at high frequencies when the bass is suspended). This is a feature of utmost importance, as it affects the instrument's playability, whether there is a gain in sound radiation to the hall or not.

It should be noticed that the bridge mobility is directly related to the strings' damping and is extremely influential in this respect: The reflection factor at the bridge for the *n*th partial is given by $\Lambda(n) = [Z_0 - Z(n)_{\mathrm{BRIDGE}}]/[Z_0 + Z(n)_{\mathrm{BRIDGE}}]$, where Z_0 denotes the characteristic wave resistance of the string, and $Z(n)_{\mathrm{BRIDGE}}$ denotes the magnitude of the bridge impedance at the partial frequency, n ($n = 1, 2, 3,\ldots$). Had this been the only loss of the system, the system's loss factors could have been written $\eta(n) = \ln|\Lambda(n)^{-1}|/(n\pi)$. For $Z_0 \ll Z(n)_{\mathrm{BRIDGE}}$, $\eta(n)$ is thus nearly proportional to $1 - \Lambda(n)$, and to $Z(n)_{\mathrm{BRIDGE}}{}^{-1}$, i.e., the bridge *mobility*. With the bridge as the major element of drainage, it goes without saying that a 3 dB increase in bridge mobility nearly implies a loss-factor doubling—or a 50% reduction of *Q*-value. Increased mobility would affect the transients, particularly the attacks, where the entire instrument would be felt more benign and compliant. With less of the transient signal firing back from the body to the strings, the bow–string interaction will be perceived as easier to control. Further support for the importance of changes in bridge mobility due to the supporting floor can be taken from string design. It is a well-known fact that the damping is a crucial design parameter for playability.

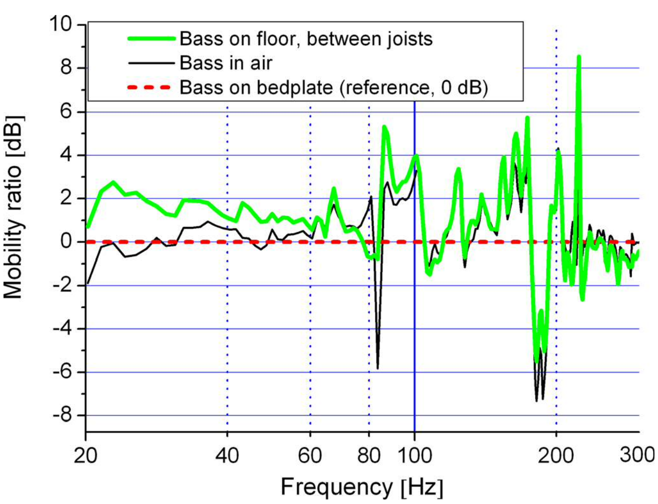

FIG. 9. (Color online) Changes in bridge mobility caused by the support of the end pin. The foundation under the end pin plays an important role for the playability of the double bass through the impact on the bridge mobility. Bridge mobility of a large five-string bass in LiH, measured with the end pin resting on rigid bedplate (0 dB reference); on the stage floor between joists (thick line), and bass suspended in the air (thin line).

V. PROPERTIES OF FIVE STAGE FLOORS

As discussed earlier, five concert halls were studied with respect to the properties of the stage floor: OCH (opened in 1977), BwH (1979), LiH (1988), NORH (2008), and NOOP (2008).

The impedances of the stage floors of the five halls were measured. In order to compare the floors, it is necessary to separate the most pliant sections of each floor from the most rigid ones. The most pliant sections were all found between joists (on the stage/pit lifts of BwH, OCH, and NOOP), while the most rigid sections were found on the parquet glued to concrete/bedrock (the old floor of BwH), on the parquet fastened to plywood and glued to concrete (the stage wings of OCH), or simply on the joists (LiH, NORH, and NOOP). As evident from the following description, the floors were designed with quite different concepts. As far as we know, none of the stage lifts has any damping material attached, or an extended cavity below.

A. Briefly about the floor designs

1. LiH

The stage floor (22 mm Merbau parquet) is rather pliant, also on top of the joists. The joists, 30 cm apart and resting on thin rubber blocks, support the floor 5–6 cm above a floating concrete floor with the cavity in between filled with rock wool (see Fig. 1). The stage is about 170 m^2. The hall is very well thought of for orchestra bass playing.

2. BwH

The entire wooden floor (Muninga) was originally glued to a concrete foundation resting on bedrock with hot asphalt. The whole stage, except the outermost wings, has been rebuilt. Sections, including those where the basses are positioned, were replaced by stage lifts (220×140 cm) constructed with parquet tops (Muninga) resting on wooden ribs about 5 mm above the steel plate. There was no damping material in the small sealed cavity.

3. OCH

This hall was designed with lifts in the center and at the rear of the stage, but not where the basses normally were seated, i.e., on the right wing as seen from the audience. The wing floor should have been built with a small cavity below, but, according to our knowledge, the cavity was dropped for architectural, not acoustical, reasons. Instead, the parquet flooring (Merbau) was fastened to plywood, which was glued with hot asphalt to the concrete floor. The paradoxical situation occurred that when the basses moved forward for repertory demanding smaller ensembles, they would enter one of the lifts, and the depth of the bass sound was suddenly experienced to increase. Nowadays, the bass group is normally placed on the rear lifts, or on portable risers when seated on the wings.

4. NORH

The floor of this rehearsal and recording hall is 22 mm Oregon pine parquet on 25 mm birch plywood supported by randomly separated joists resting on floating concrete with no damping in between. The joist interval is quasi-randomly varying between 40 and 60 cm to avoid resonances.

5. NOOP

The entire pit floor is mounted on a three-piece hydraulic lift where joists (200 × 95 mm, resting on steel beams) are mounted quasi-randomly with as much as 160 cm separation on average (and extra non-touching joists in between to prepare for heavy loads). The floor is a 45 mm laminate. There is no particular damping apart from the beam spacing. Bassists are quite happy with the playing conditions in the pit, where the floor appears "lively."

B. Measurements of stage-floor impedance

All impedance measurements were executed with calibrated Brüel & Kjær accelerometers and impact hammers. The floor was at all times loaded by the weight of the person measuring, substituting for a bass player. Apart from deriving magnitude and phase, decay times and loss factors were calculated in 1/3-octave bands, wherever possible. Impedances and loss factors for LiH, OCH, and BwH are given in Table II, together with the linearized bass impedance for comparison (see Fig. 7).

For BwH and OCH the result of the calculations of the rigid areas proved too noisy due to very high impedances. As evident from Fig. 10, there is a great difference between the impedances of the rigid and the pliant sections for most floors. The exception is LiH with low joists resting on thin rubber blocks.

Figure 10, upper panel, shows that there is a noticeable spread in the rigid-area impedances, from about 4000 kg/s (36 dB) for LiH, to 79 000 kg/s (49 dB) for OCH at 60 Hz. The floor impedances of NORH and NOOP (not shown in the plot) followed the curve of OCH well, but shifted down a few decibels. BwH, with the bedrock foundation, gives an impressing impedance of 12.6×10^6 kg/s: (71 dB). With the exception of BwH, the phase angles lie around −90° (spring dominated) to −130°. OCH shows some resonant activity in the range 20–40 Hz, most likely as a result of the plywood/parquet coming loose from the concrete at certain places. An important observation is that LiH is the only hall that provides matching impedance with the double basses below 100 Hz.

Figure 10, lower panel, shows the corresponding impedances measured at the pliant areas of the stage floors. The values range from 500 to 12 600 kg/s at 60 Hz (a factor 25, just like for the impedance cluster for the rigid sections). This time NOOP and NORH (not shown in the plot) were located about 2 and 5 dB above OCH in the range 20–100 Hz, respectively. Again the BwH stands out, but now showing the lowest impedance of all stages, as well as a small resonance around 60 Hz. In this case all floors have matching impedances below 100 Hz, although the exact match point varies from 28 Hz (BwH) to 84 Hz (NORH). Below 100 Hz, the floor impedances can be approximated by a straight line in Fig. 10 with a slope of −3 dB/octave ("linearized floor").

C. Vibration transfer from bass to floor

The significance of the impedance relations bass and floor can be understood when studying Fig. 11. In the upper panel, the velocity transfer from end pin to floor is shown for the "linearized bass" on the "linearized floor" with impedances rising/falling with averaged values of + 4.3 and −3 dB/octave below 100 Hz, respectively. The abscissa is normalized around the frequency of matching impedance magnitudes. The phase differences play a crucial role. The closer the phase difference comes to 180° (bass + 90°, floor −90°) the higher the resonant peak around the matching frequency

TABLE II. Loss factors and impedances of the three stage floors with the greatest potential of radiating low-frequency bass sound. All measurements were done at pliant sections.[a,b]

	Loss factor			Impedance magn. (kg/s)			Impedance phase (deg.)			Double bass	
Freq. band (Hz)	LiH	OCH	BwH	LiH	OCH	BwH	LiH	OCH	BwH	Imp. (kg/s)	Phase (deg)
20	0.313	0.376*	0.149	3554	12551	1711	−124	−98	−109	1000	90
25	0.347	0.523*	0.387	3293	10587	**1888**	−126	−100	−112	2286	90
31	0.371	0.547*	0.535	**3155**	8405	1199	−129	−105	−107	3571	90
40	0.397	0.519*	0.287	3090	7068	868	−129	−100	−119	4857	90
50	0.402	0.542	0.199	2785	**5290**	608	−128	−98	−137	6143	90
63	0.639	0.522	0.149	2208	3974	658	−135	−101	−188	7429	90
80	0.320	0.144	0.109	2434	2910	875	−157	−103	−192	8714	75
100	0.211	0.088	0.079	2985	2005	1324	−151	−112	−205	10000	-125
125	0.327	0.082	0.162	2995	2198	1805	−156	−151	−182	10000	−126
160	0.204	0.106	0.124	3487	2182	1466	−152	−131	−175	Descending impedances with higher frequencies	
200	0.153	0.096	0.138	3465	1679	1467	−142	−139	−178		
250	0.229	0.081	0.125	3274	1657	1244	−146	−170	−177		
320	0.142	0.072	0.223	2754	2032	1749	−125	−161	−176		
400	0.115	0.069	0.258	2472	1933	1321	−140	−160	−162		
500	0.091	0.067	0.438	2521	1790	1155	−141	−169	−169		

[a]An asterisk (*) indicates calculations based on the early-decay-time slope (0 to −10 dB).
[b] Bold digits indicate impedances matching most closely those of the linearized double bass for each floor.

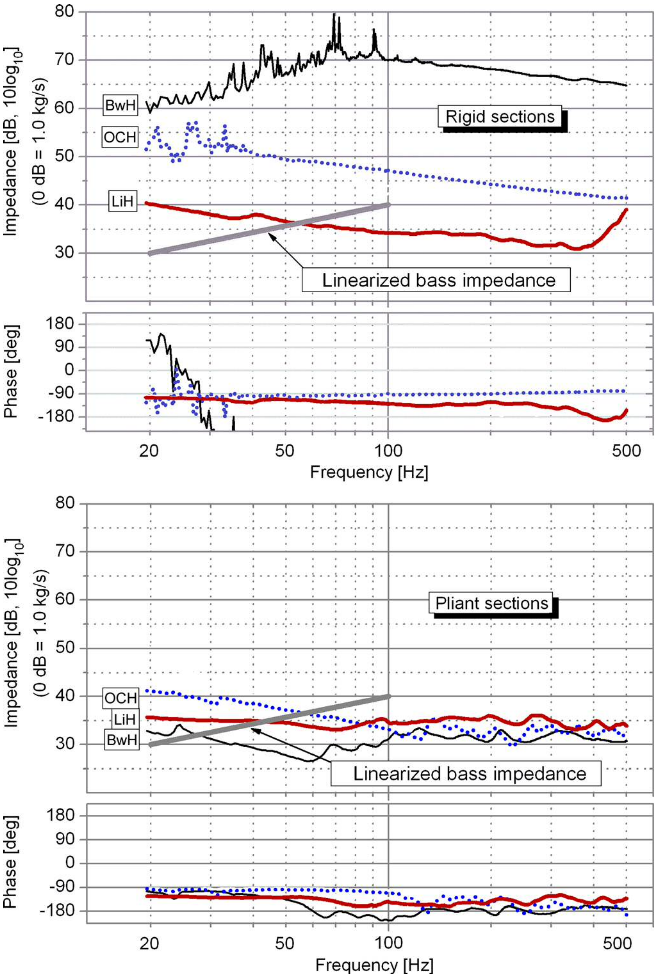

FIG. 10. (Color online) Impedances of the rigid and pliant sections of three of the five stage floors (upper and lower panels, respectively). Linearized double-bass impedance at end pin is indicated (thick gray line) in the range 20–100 Hz for comparison. Only LiH (thick line) is providing an impedance of matching magnitude in the rigid section. In the pliant sections, impedances of matching magnitude are found for all the floors, but at different frequencies. The phase is almost constant at $-90°$ to $-130°$ below 60 Hz for all floors.

becomes, below which the transfer function is rapidly rolling off. In other words, the impedance magnitudes should ideally cross at the lowest frequency where a good transfer is desirable, because below this frequency the transfer function will roll off with a slope of about 9 dB/octave under the given properties. This result is clearly seen in the lower panel, where transfer functions for the large four-stringed bass and the three of the five floors are calculated by use of Eq. (3) and their respective, measured impedances. The transfer curves of OCH, LiH, and BwH start rolling off at $\sim$ 60, 30, and 20 Hz, respectively, and it is seen that OCH and BwH have very high peaks above their roll-off frequencies due to the relative phase values, bass and floor. NOOP and NORH (not shown in the plot) roll off at about 50 and 60 Hz, respectively, also these with high peaks right above. Typically, the floor of LiH, with impedance match at 44 Hz and phase near $-130°$ (in contrast to the $\sim\!-100°$ of the others), appears significantly more damped, and the resulting peak above roll-off consequently more moderate.

One should expect very high peaks in the transfer function to produce unwanted colorization ("barrel sound"), particularly during onset transients. The smaller peaks of the LiH transfer can be recognized as mainly related to the genuine resonances of the double bass itself and should not create any effect of this kind. (Compare the impedance notches of the four-string bass of Fig. 7 to the LiH transfer curve in Fig. 11, lower panel.)

The corresponding transfer functions for the rigid sections show that only LiH gives transfer values above 0 dB (with roll off below 33 Hz), while of the remaining halls, NOOP gave the highest values (about 10 dB lower than LiH, with roll off below 54 Hz).

VI. EVIDENCE OF THE TABLETOP EFFECT

A full-scale experiment was run in LiH and BwH to verify the prominence of the tabletop effect under authentic conditions. A double bass was "played" by exciting the bridge by a shaker, and the sound pressure was measured in the audience area with (1) the bass supported as normal on the floor, and (2) with the bass not in contact with the floor. In order to estimate the contribution of the floor vibrations to the total sound pressure of the hall, a setup that included an efficient insulation between the bass and the floor was of utmost importance. We chose to do this in two ways: (a) By supporting the bass on a rigid foundation below the floor through a hole in the parquet. In the BwH this was done by cutting a hole in the riser's steel plate as well in order to support a 60 cm solid iron rod (diameter 40 mm) on the concrete foundation. In LiH the bass' end pin of steel could reach down to the bedplate through the slit between the floating concrete blocks (see Fig. 1). (b) By raising the bass' end pin above the parquet, having the instrument suspended in rubber bands inside a wooden frame. The frame, with base dimensions 90×45 cm, was insulated from the floor using soft foam rubber cushions (thickness 11 cm unloaded).

The frame also held a heavy shaker (mass about 5 kg) for driving the bridge, and was utilized in all experiments, also when the bass was resting with the end pin on the floor. The shaker excited the bridge in the bowing direction at the low E string side via a 5 cm stinger of piano wire (diameter 1 mm). The bass maintain a fixed position on stage throughout all experiments. The basses utilized for the experiments were both large five-string Pöllmann basses (in BwH the same instrument as in the impedance measurements).

The experimental setup included two accelerometers, one next to the driving point of the shaker at the bridge, and one on the floor next to the bass end pin. An omnidirectional studio microphone (BK4007) was placed at the same seven positions in the hall utilized earlier (near field + 6 in the audience area). In this way we could estimate not only the transfer function—sound pressure/bridge velocity, but we could also estimate a maximum contribution from the floor, because both its vibrational velocity and its transfer functions (point-driven floor to sound pressure in the hall) were known. The results for LiH and BwH are presented in Fig. 12, left and right columns, respectively.

The upper panels of Fig. 12 show a comparison of the averaged sound pressure levels in LiH (left column) and BwH (right column) with the bass on the stage floor as

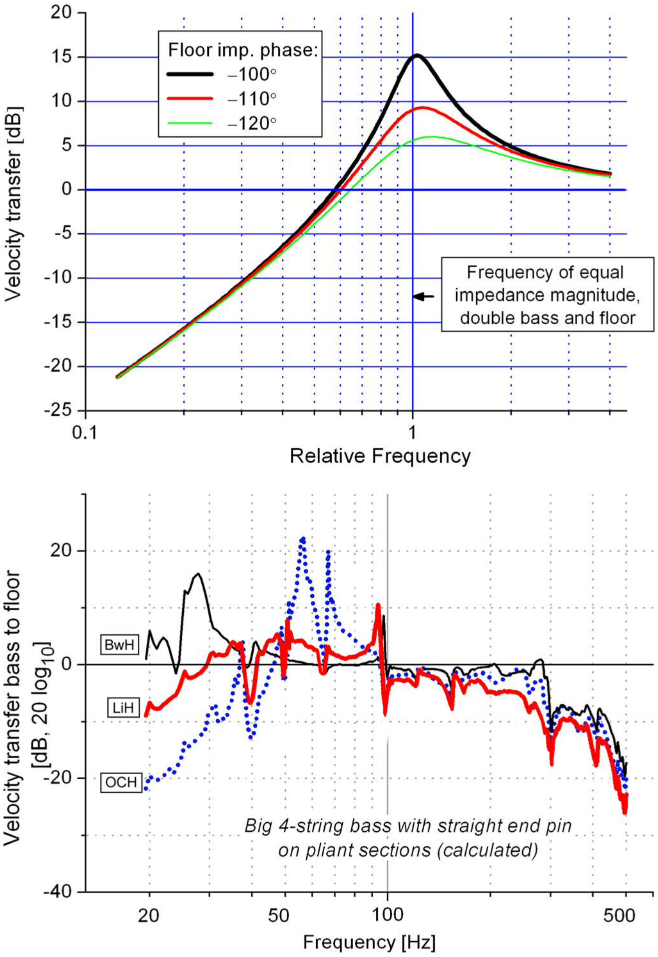

FIG. 11. (Color online) Upper panel: Effect of the phase of the floor impedance on the transfer function, end pin to floor, around the frequency of matching impedance magnitude. The phase of the linearized bass impedance is at all times considered to be 90° (mass). The linearized floor impedance falls −3 dB/octave with phase −100°, −110°, and −120° (thick, medium, and thin line, respectively). Lower panel: Calculated transfer functions for the large four-stringed bass on three different stage floors in their pliant areas. High peaks are seen for OCH and BwH, while LiH, due to the greater damping (phase $< -120°$), shows a flatter curve above the roll-off frequency, ∼30 Hz.

normal, freely suspended in the air, and supported on rigid foundation (bedplate), respectively. The comparison is made using the rigid foundation condition as reference (0 dB). In LiH the sound pressure curve is steadily rising below 80 Hz, and between 40 and 60 Hz the gain is about 5 dB compared to the rigid reference case. Between 30 and 40 Hz the gain is even higher, exceeding 10 dB. (If one prefers to view these ratios in the perspective of transmission from bridge *force* to sound pressure, simply add the decibel values of Fig. 9 to the corresponding values in the upper left panel of Fig. 12.) While such an effect could be expected with the bass on the stage floor (indicating the desirable tuning fork–tabletop effect), it was a notable observation that the suspended bass showed great projection for certain frequency bands, including the 30–40 Hz band. Similar results were obtained in BwH, even more pronounced, and with the use of a different bass (see Sec. VII).

The three lower panels in Fig. 12 (only two in the right column) show the transfer functions for averaged sound pressure in the hall vs bridge velocity under the three supporting conditions. The calculated maximal contribution from the stage floor to the sound in the hall is included for comparison (thin black curve). This contribution is computed as $(V_{\text{FloorBass}}/V_{\text{Bridge}}) \cdot (P_{\text{Hall}}/V_{\text{Floor}})$, where the first ratio is determined from the values of the two accelerometers, while the second ratio denotes the transfer from the point-driven floor to sound pressure in the hall. The condition "Bass on floor" (second panel) is particularly interesting. Here the contribution from the stage floor sets the total sound level below 40 Hz. In this case the floor is excited in the most efficient way with respect to radiation—in a single point, through the bass' end pin.

The calculated contributions from the stage floor in the "Bass in air" and Bass on bedplate" conditions are due to coupling between the bass corpus and the floor through the air, and traces of the vibrations in the wooden frame leaking through the foam rubber cushions. Below 30 Hz, this contribution to the sound radiation is at least 10 dB weaker than with the bass on the floor, and decreases rapidly towards higher frequencies.

Several interesting details are observable in the data from BwH, right column of Fig. 12 (the Bass on bedplate condition not included due to inaccessible data). The comparison between averaged sound pressure levels in the hall (upper panel) shows that the suspended bass provided much better low-frequency response compared to the reference condition with bass on bedplate (about 5 dB between 30 and 50 Hz). A little surprising, the sound radiation in BwH hardly benefited from the wooden parquet on the lift at all, staying close to 0 dB below 100 Hz. The radiation was even lower than for the rigid reference condition below 40 Hz. This was also the clear impression when listening to the sweeps during recording.

When further examining the total sound pressure with the bass on the floor in BwH (second panel, thick line), it can be noticed that this curve has a 5 dB dip at 40 Hz, while in the same region the curve for maximum contribution from floor lies more than 0 dB above the total sound pressure. This observation suggests that the radiation from bass and floor is out of phase in this region. This assumption is supported by the condition with the bass in air (lower panel). The total sound pressure curve is quite similar to the curve in the panel above, but the 5 dB dip is absent, at the same time as the maximal contribution from the floor is much weaker. The results indicate that it is absolutely not given that floor vibrations will provide favorable phase conditions.

VII. DISCUSSION AND CONCLUSIONS

This study has scrutinized the necessary conditions for a boosting of the low-frequency double-bass sound by radiation from the stage floor. The entire path from the instrument's body vibration, via the floor, to the sound field at a number places in the audience has been studied. It is evident that a "tuning fork–tabletop effect" can occur under favorable conditions. The LiH provides a successful example. In the deep bass range where the double bass is a particularly poor radiator (between 30 and 60 Hz), and up to about 100 Hz, our results show that the conditions for an efficient transmission of vibrations from the end pin to the stage floor

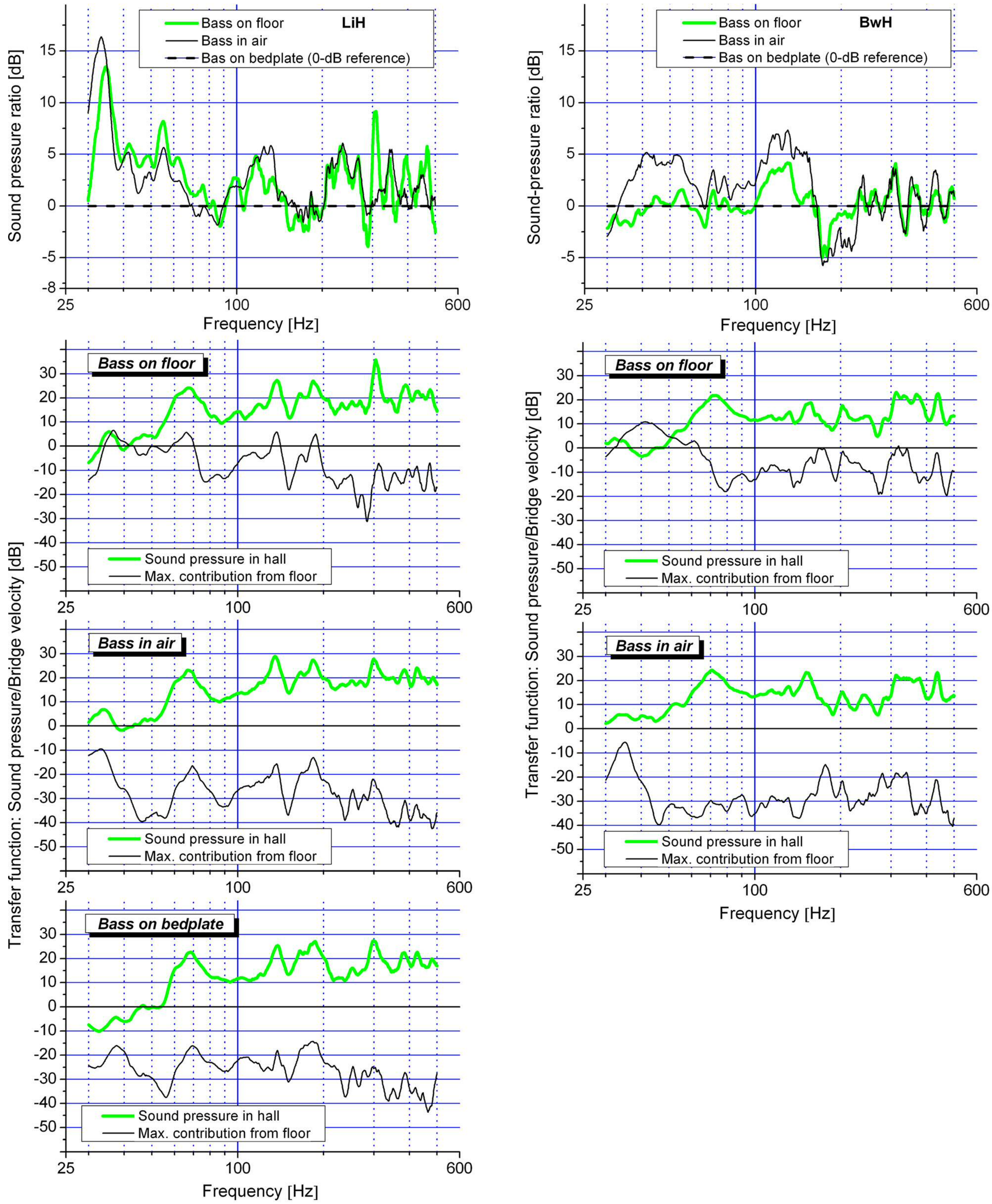

FIG. 12. (Color online) Upper panels: Ratio between sound radiations in LiH (left column) and BwH (right column) as function of bridge velocity for the bass on the floor (thick line), and the bass in the air (thin line), both compared to the bass resting on the bedplate (reference 0 dB). Lower three panels: Measured transfer functions, sound pressure/bridge velocity with the bass on floor, suspended in the air, and on bedplate (thick lines).The calculated maximum contributions to the total sound from the floor are indicated (thin lines).

and radiation into the far field in the hall are fulfilled in this hall. These findings support the opinions expressed by bass players (and by other musicians and audience as well) that the hall has a very satisfying sound from the double basses—deep, but still transparent, and well balanced.

LiH was chosen as a case study for our comprehensive experiments because it had the best potential of confirming the effect. One should not jump to conclusions about the other halls as long as information about the radiation efficiencies is lacking. That being said, it is obvious that a prerequisite is a reasonable transfer of end pin vibrations to the floor in the frequency range of interest. In our measurements, NORP and NOOP disqualify themselves already here, while OCH singles out as dubious. It would thus clearly be of interest to further measure the radiation efficiency in the remaining hall, BwH. According to the measurements of the vibration transfer to the floor (see Fig. 11, lower panel), BwH seems to have a high potential for supporting the deep bass sound provided that the radiation efficiency is sufficiently high. When the measured floor contribution appeared not so favorable (see Fig. 12), it may have been caused by the wooden frame used to hold the bass upright. We noticed that compared to the floor/bridge velocity transfer shown in Fig. 8 (where the bass was held as in normal playing by a musician), a considerable damping of the floor took place when the wooden frame with the shaker was resting on the stage lift with its footprint surrounding the end pin's contact point at the floor. When utilizing this wooden construction a transfer drop of about -10 to -25 dB was observed below 40 Hz, both in BwH and LiH. Without this damping, the low-frequency radiation of the floor in BwH might have surpassed the limited radiation of the bass itself to a degree that phase mismatch was no longer an issue. On the other hand, each stage lift in BwH is normally occupied by two bass players with music stands and heavy stools, which do have an impairing effect on the stage-floor vibration in practice. Our measurements can thus be considered to reflect reasonably realistic conditions.

While the stage floors in concert halls differ widely in design philosophy and construction principles, and consequently also regarding the conditions for a clear tuning fork–tabletop effect, double basses seem similar in this respect. Basses differ greatly in shapes and sizes, but according to our measurements not in end pin impedances below 80 Hz, where the impedance is strongly related to their mass. The typical double bass has an impedance peak close to 100 Hz, below and above which it acts as a mass and a spring, respectively.

The large influence of the support under the end pin on the bridge mobility, which is perceived by the player as a change in "playability," can be taken advantage of in practice. In order to be able to perform under as identical conditions as possible a touring solo bass player may bring a quite small riser to ensure familiar performance conditions, The riser may be too small to contribute to the sound radiation significantly, but the playability aspect will be met.

The observation that the averaged sound pressure in the hall increased markedly when the bass was hanging in rubber bands and even reached higher values than supported on the favorable stage floor in LiH may seem surprising. However, all bowed instruments share a peculiar property with regard to their radiation at low frequencies. In contrast to the expected behavior of an omnidirectional monopole radiator in the lowest frequency range with a fall off of -12 dB/oct below the Helmholtz resonance, a dipole radiation takes over.[17] This radiation component increases with decreasing frequency as $1/\omega^2$. The dipole moment is generated when the bass moves rigidly back and forth as a whole, resembling a ping-pong racket. It is thus no surprise that the dipole radiation springs up when the end pin is released from the floor and the whole body can move freely. For obvious practical reasons the increased radiation from the freely suspended bass is not a very useful property. However, it is a clear indication of how much the bass corpus is affected by the restriction of the end pin motion when the bass is supported.

Design of stage floors in new concert halls should preferably take advantage of the increased understanding of the acoustical effect of the stage floor on the deep bass sound. Apart from the acoustical effects as such, which enriches the sound in the hall and pleases the audience, more satisfying performance conditions facilitate ensemble playing and stimulate the musicians.

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