



Experimental comparison of various excitation and acquisition techniques for modal analysis of violins



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ABSTRACT

For decades, modal analysis has been a tool to gain insights in the vibrational and acoustical behavior of music instruments. This study provides a critical comparison of various experimental modal analysis approaches with the violin as a case study. Both contact and non-contact excitation and different acquisition approaches are considered. The influence of different boundary conditions (clamped, supported, free/free) on the vibrational response of the violin is investigated. The response is analyzed to extract relevant modal parameters (frequency, damping and mode shape) within the frequency range of 0–1000 Hz. The performance of the different approaches is evaluated in terms of (i) signature vibration modes, (ii) experimental reproducibility, (iii) contact requirement and (iv) cost of required equipment. Two optimal approaches are proposed for performing modal analysis on violins: a contact method for use in the violinmaker's practice, and a non-contact method for use with fragile instruments.

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1. Introduction

You are not allowed to use any measurement method that includes a risk of damage to this valuable instrument. This declaration, or a similar statement, is a very familiar ethical directive to researchers working with valuable (historical) music instruments. Although this restriction is necessary to preserve these unique items for future generations, it may hinder our understanding of how these instruments were built, how they sound, and the link between the two. Especially in the field of vibrations and acoustics, the instrument must be 'excited' in some way to study its behavior. Sometimes, historical instruments are allowed to be played by professional musicians in listening or playing tests, giving us access to psycho-acoustic data [8,9,10,11,14,26]. However, not all instruments are in a condition which allows them to be played by a musician. Additionally, as each violin player has his/her own technique, the player is a possible confounder in each experiment. Therefore, many researchers prefer to perform measurements without the involvement of a musician. To study how these instruments 'make' sound, they have been studied from a physical perspective for decades [17,21]. Indeed, each acoustic bowed

instrument has its unique body shell vibrational response that directly contributes to the radiated sound [35,12].

Experimental modal analysis is a common tool to study the vibrational behavior of soundboard instruments like the violin [21,3,4,28–29,30,24,19,6]. The method has increased our understanding on the vibro-acoustical behavior of both conventional and experimental instruments [4,6]. For the violin, this has resulted in a nomenclature of specific signature modes, called: A0, A1, B0, CBR (or C1) B1- (or C2) and B1+ (or C3) in the 0–1 kHz range [4,25]. Fig. 1 shows a typical frequency response function in this frequency range with indication of the signature modes' resonance frequencies and nodal lines. The A0 mode corresponds to the first air resonance mode or Helmholtz resonance of the sound box, and has a strong acoustic radiation. The A1 is the second air resonance and first longitudinal mode. According to Bisssinger [4] it is 'sometimes an important radiator'. The B0 mode is the first corpus mode associated with a bending between the neck and sound box of the instrument. The B1- and B1+ modes are corpus bending modes that radiate strongly. The CBR mode, or Center Bout Rotation is a corpus mode with a shear-like motion between the top and back plate. It has a relatively low acoustic radiation. Above 1 kHz, the frequency response of violins is studied more globally by examining phenomena over a frequency range such as the bridge hill [15].

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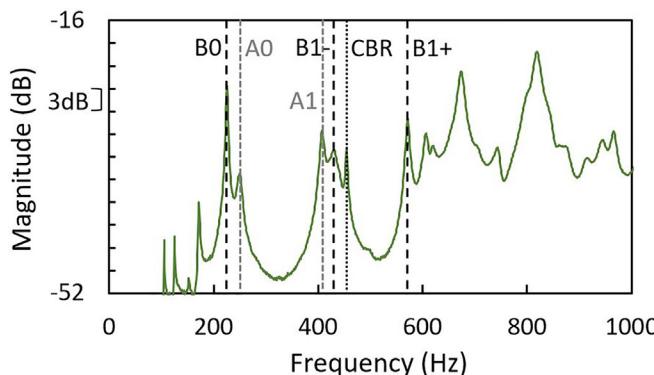


Fig. 1. Frequency response function and signature modes (dotted lines) of a carbon violin top plate. From left to right: B0, A0, A1, B1-, CBR and B1 + . Signature modes that contain nodal lines (white lines) on the top plate are displayed on the right.

The current standard method to perform a modal analysis on violins includes exciting the instrument with an impact hammer and measuring the response with a lightweight accelerometer or a more expensive laser Doppler vibrometer [3,4,19,28–29,30,6].

Pyrkosz and Karsen [24] investigated the use of two common types of excitation on the bridge of the violin between 100 and 800 Hz: the impact hammer and the electromagnetic shaker. They found both methods to have their benefits and limitations. The shaker results in less noise, but introduces significant mass loading issues and correct choice of the stinger location on the violin is not straightforward. For the impact hammer on the other hand, the tip had to be replaced by a custom acetal plastic tip in order to reduce the risk of damage to the instrument. This obviously complicates the proper excitation of a broadband signal in the violin. Furthermore, a consistent measurement with the impact hammer is highly dependent on the skill of the hammer operator (e.g. double impacts). Due to the difficulty of having consistently similar hits, the impact hammer method results in limited repeatability of the measurement [24]. Moreover, excitation through impact hammer includes a risk of damage to the instrument, which is not acceptable in the case of fragile violins.

There are other excitation alternatives of interest such as: piezo elements, acoustic speakers, pressurized air and the roving wire-breaking technique. Piezoelectric actuators elements (PZT, lead zirconate titanate) are a common excitation tool to perform vibration analysis [5]. However there are no publications that investigate the use of PZT's for modal analysis of a violin. Speaker excitation is sometimes used by violinmakers to find and tune the modes of violin plates to a certain frequency before assembly [13,16], or as an education tool in violinmaking schools. Acoustic excitation has been used to study the effect of traditional violin varnish layers on rectangular spruce plates [18] and by Viala et al. [33] to study a flax composite soundboard for a violin. However, it is not an excitation method usually considered to perform a modal analysis on violins as the actual input signal to the violin is unknown. The use of pressurized air as an actuator for a modal analysis has been shown to be a valid method to excite small structures up to 1000 Hz [31], but pressurized air is not a common excitation method for modal analysis. The roving wire-breaking technique (also known as the step relaxation method) has been introduced as a cost effective excitation method for bridge mobility measurements on guitars [22]. The drawback of this excitation method for modal analysis is that it is very time consuming, and therefore only suitable if a low number of measurement points are investigated. In the case of modal analysis on violins, a high number of measurement points are needed in order to correctly identify the signature mode shapes. We found approximately 150 points to be the minimum, although this depends on the experience of the researcher in

question. If one wants to identify the shape of modes that are higher in frequency than the signature modes, more measurement points are recommended.

Although acquisition with a lightweight accelerometer is common to perform modal analysis of violins, it has been shown to be a possible confounder between experiments. Vanwallegem et al. [32] reported that the position, mass and the wiring of the accelerometer can have a significant impact on vibration measurements. Instead, there are more advanced acquisition procedures by making use of (scanning) laser Doppler vibrometry (SLDV) [3]. This is a non-contact sensing approach, and therefore the sensitivity and signal-to-noise ratio is somewhat lower compared to an accelerometer mounted on the surface of the violin (especially considering the typical glossy surface finish of many violins). Experiments on a Persian setar revealed acquisition through an LDV to be preferred over an accelerometer, yet the authors stated 'a lightweight accelerometer can still be used with some care' [20].

The goal of this study is to develop a reliable no-risk method to perform modal analyses on music instruments. Various methods to perform experimental modal analyses on violins are presented. Different acquisition and excitation methods are compared, as well as the effect of boundary conditions on the vibrational modes of a violin. Finally, the most suitable method will be used to perform a modal analysis on a fragile handmade wooden violin (Fig. 2).

The optimal method for a modal analysis experiment is determined by the context of the measurement: the value of the

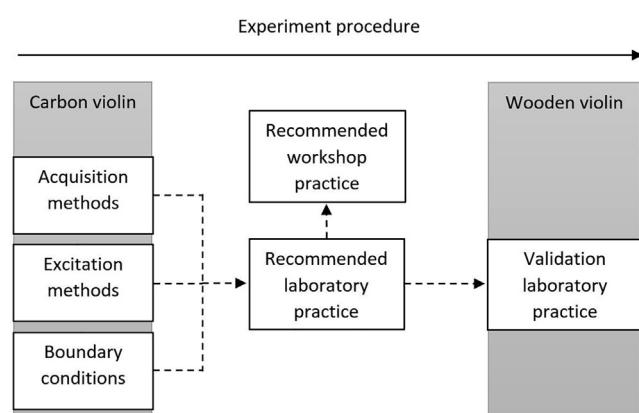


Fig. 2. Overview of the presented experiments. First, a variety of experimental approaches are investigated on a carbon violin. Based on these results a recommendation for laboratory and workshop research practice is proposed. The non-contact laboratory practice is then validated by performing an experiment on a fragile wooden violin.

instrument, available equipment and budget. As such, the modal analysis methods are evaluated with two practices in mind:

1. Workshop practice

In order to be practical for violinmakers to use in their workshop to conduct research, measuring equipment must be relatively cheap and measurements must be reliable. The method should be suited for repetition in various stages of the construction process in or near the violinmaker's workshop.

2. Laboratory practice

In many cases, such as with historical instruments or contemporary violins with a fragile varnish, even a small risk of damage is unacceptable. The first prerequisite is the preservation of the instrument. A complete contactless method is preferred. This method can be more expensive and can require a more controlled laboratory environment in order to achieve reliable measurements.

2. Materials and methods

2.1. Violins

Carbon violin: A violin made out of carbon fiber reinforced polymer is used for most measurements as it is less likely to be damaged during the experiments than a conventional violin. The violin was made through vacuum assisted resin transfer method (VARTM) [7]. An added benefit of using a carbon violin is that it is less likely to be affected by changes in air humidity that can alter its vibrational behavior between experiments [18,34].

Contemporary violin (2012): The more fragile wooden violin used was handmade by a luthier in 2012. The design and construction of this contemporary violin was based on the model of the Stradivarius 'Messiah' violin (1716). This more delicate violin is used in order to further investigate the viability and safety of our proposed method.

Both violins were examined with strings in tension tuned to 440 Hz and damped using a folded tissue at the lower part of the neck.

2.2. Hardware

Excitation: Different excitation approaches are employed (Fig. 3): (a) A miniature impact hammer (PCB 086E80). The impact hammer excited the instrument on the top plate using a pendulum

motion, for which a ball bearing was used. We used an aluminum handle PCB 084A17 and a hard metal tip as preliminary tests showed this resulted in the best input signal. (b) Electromagnetic shaker (Bruél & Kjaer LDS V406). The shaker is attached to the inside of the c-bout of the instrument with a stinger. The stinger is mounted on the violin using bee-wax. (c) Piezo element (PI ceramic DuraAct P-876.A15 and P-876.A12). The piezo element is attached to the back at the flattest part of the arching with double-sided tape. (d) Acoustic excitation through a speaker (RCF MR 88). The speaker is placed at a distance of approximately 6 cm from the violin, facing the backside of the instrument in the 0° position; Experiments were conducted with various angles of the speaker relative to the violin: 0°, 45°, 90° and 135° (rotating clockwise in the transverse plane). For the case of piezoelectric patch excitation and speaker excitation, the excitation signal produced by an arbitrary wave generator is amplified by a high voltage, wide bandwidth laboratory amplifier (Falco WMA-300) to a voltage of respectively 50 Vpp and 30 Vpp.

Acquisition: The response signal is measured with a lightweight accelerometer or a scanning laser Doppler vibrometer (SLDV), a table comparing both methods is displayed in Table 1. The lightweight accelerometer is mounted with bee-wax in the lower bout on the top plate on the right of the tailpiece. The acquisition through SLDV was automatic, resulting in a total measurement time of 17 min when combined with excitation through an arbitrary wave generator. Both the PSV scanning heads and the lightweight accelerometer are directly connected to the Polytec PSV-W-500 data management system. The acquired data is finally analyzed by the PolyMAX [23] algorithm software (Testlab LMS 17) in order to extract modal parameters, i.e. resonance frequency which we rounded to 1 Hz, damping and modal shape.

Boundary conditions (Fig. 4): Different boundary conditions are considered. (a) Free-free: the violin is hung by elastic rubber bands attached to (i) the neck and (ii) the nylon loop which connects the tailpiece with the end-button. (b) Clamped-neck: a round vise is used to clamp the violin by the neck at the position a violin player would place his/her fingers during playing in first position. (c) Violin stand: the violin is supported by a common violin stand on the instruments bottom, lower edges of the front and back (GEWA Violin Stand BSX).

2.3. Criteria

To evaluate the performance of the different experimental modal analysis approaches, the following criteria are used:

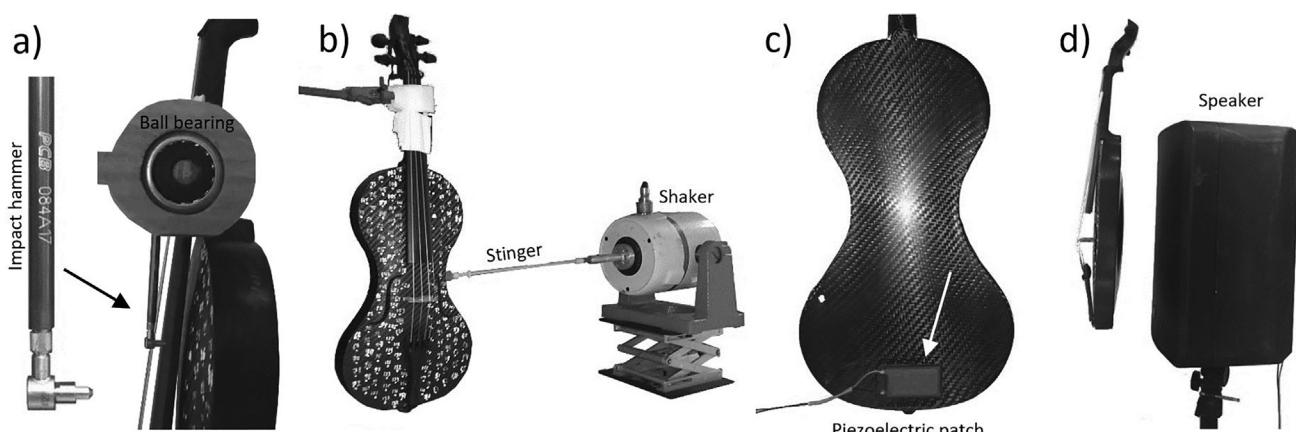


Fig. 3. Excitation methods: (a) impact hammer (PCB 086E80), (b) electromagnetic shaker, (c) piezoelectric patch and (d) acoustic speaker excitation (0°position).

Table 1

Acquisition methods: lightweight accelerometer mounted with bee-wax, contactless SLDV.

	model	mass	Measurement points	Complex Averages	Freq. resolution
Lightweight Accelerometer SLDV	PCB 325C65	2 g	160	3	~1 Hz
	PolytecPSV-500 Xtra	-	211	3	~1 Hz

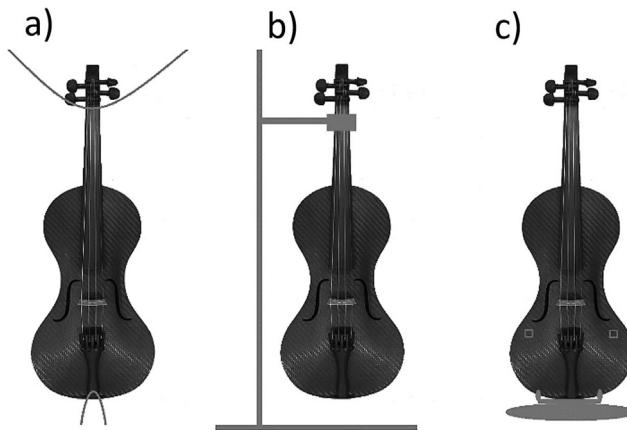


Fig. 4. Boundary conditions: (a) free-free, (b) clamped-neck and (c) violin stand.

- (1) The coherence function of the Frequency Response Functions (FRF's) must be consistently above 0.8. As such, the obtained FRF's can be considered repeatable and reproducible.
- (2) The signature modes must be found: B0, A0, A1, B1-, CBR, B1+.
- (3) The modal parameters, i.e. resonance frequency (Hz) and damping (%) of the signature modes must have sufficient consistency between measurements in order to allow comparison between instruments. Previous research showed that support fixture damping induced by the violin player outweighs the internal damping [4]. However, the damping of signature modes combined with radiation measurements can provide insights in how efficiently sound is radiated by these modes for various instruments.
- (4) The method with the lowest risk of damage to the instrument is preferred for the laboratory practice. Although all of the examined tests can be considered non-destructive for most industrial applications, music instruments can be very fragile. Among others, wooden violins are vulnerable to: chipping or scratching of the varnish, denting the wood, the introduction of new cracks and the (re)opening of old cracks and joints.

3. Results and discussion

3.1. Acquisition

In order to evaluate the influence of the acquisition approach, the identified signature modes are compared for a measurement using the accelerometer (roving impact hammer excitation, clamped-neck boundary condition) and for a measurement using the SLDV (fixed impact hammer excitation, clamped-neck boundary condition). Results are presented in Table 2. The difference in frequency of the modes between the two measurements is likely caused by the added mass (2.0 g) of the accelerometer: A1, and to a lesser extend B1- and CBR are slightly lower in frequency while B1+ is higher compared to the non-contact SLDV method. Signature modes are expected to drop due to mass-loading effect,

Table 2

Acquisition methods. Signature modes, frequency (Hz) and damping (%) obtained in two impact hammer excitation experiments with different acquisition methods.

	Accelerometer	SLDV
	Freq. (damping)	Freq. (damping)
B0	226 (0.76)	223 (0.8)
A0	247 (1.64)	247 (1.63)
A1	395 (1.37)	408 (1.05)
B1-	429 (1.53)	432 (1.46)
CBR	450 (0.72)	453 (0.49)
B1+	579 (0.81)	550 (0.6)

but a violin is a complex system with many natural frequencies interacting through veering. Based on our measurements we cannot clarify what causes B1+ to increase in frequency. Possibly high-level numerical simulations like those of R. Viala [33,34] are better suited to answer this question. The obtained damping of the modes are equivalent between the two methods. This indicates that if controlled experimental conditions are used, both these approaches can be used to provide estimates on the damping of signature modes. This can in turn provide insights in how these different modes influence sound production.

To verify that the frequency shift of the modes is indeed caused by the mass of the accelerometer, a different experimental modal analysis (acoustic excitation, free-free boundary condition, SLDV acquisition) was repeated three times: Once with an accelerometer mounted to the top plate and two times without (Fig. 5). The same shift in frequencies is observed, confirming that the error is caused by the lightweight accelerometer. The peaks in the average frequency spectrum below 200 Hz are rigid body modes attributed to the elastics used to suspend the violin.

When measuring the response through a lightweight accelerometer, it is important to take into account the effect of the added mass to the vibrational response of the instrument. When using this method for comparison between instruments, it is therefore essential that the same accelerometer is mounted at the same position for each instrument. Still, as violin soundboards can vary in thickness and weight (roughly between 55 g and 75 g), each violin is likely to respond differently to the added mass. In classic modal analysis it is said that the mass of the accelerometer should be lower than 10% of the vibrating object mass [2]. For modal analysis of violins this demand seems to be more strict. Acquisition through a (S)LDV is preferred, as it does not introduce errors due to mass loading.

3.2. Excitation

For the impact hammer, the quality of the induced vibrational energy is dependent on the skill of the operator. In the case of shaker, piezo and speaker excitation, specific input signals can be defined using an arbitrary wave generator. A variety of specialized waveforms have been tested, and finally a periodic chirp signal was selected as this provided the best results for all excitation methods. Further, multiple positions of the speaker relative to the violin were explored. The placement of the speaker right behind the violin at a distance of 6 cm (Fig. 3d) provided good results. It is close enough to induce sufficient energy in the violin, yet sufficiently distant to avoid air damping effects [32]. When comparing the

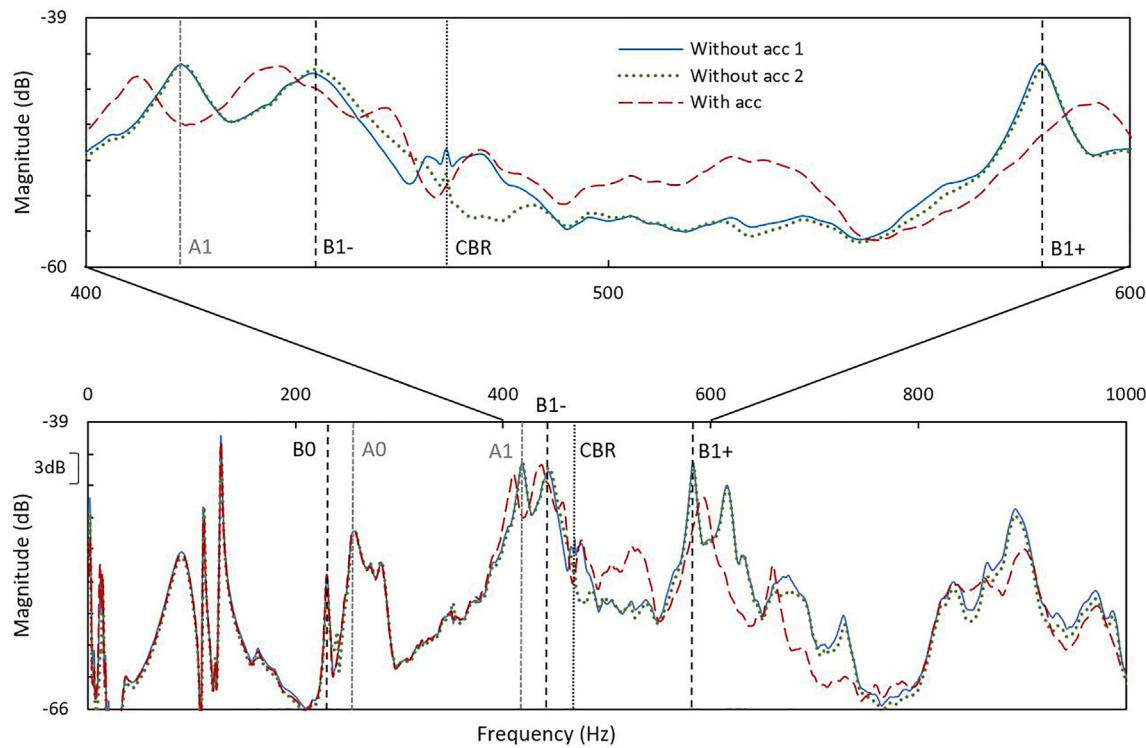


Fig. 5. Influence of an accelerometer. Average frequency response functions (FRFs) of all measurement points with and without a lightweight accelerometer attached to the soundboard (acoustic excitation, free-free, SLDV). The accelerometer causes certain modes to shift in frequency (A1, B1-, CBR and B1+) and amplitude (B1+).

coherence between the examined excitation methods (Fig. 6), speaker excitation, impact hammer and shaker excitation provide a good coherence between 50 and 1000 Hz. The piezo element has a near perfect coherence starting from 400 Hz, but is not able to excite the violin in the lower frequencies.

In Table 3 the extracted modal parameters of the **signature modes** for all excitation methods and SLDV acquisition are shown. The excitation with the piezo element did not allow the B0 and B1- mode to be identified. Our results further confirm the induced error of the shaker method [24]: The A1, B1- and CBR mode shift upwards in frequency compared to the impact hammer, the current standard excitation method for modal analysis of violins. Furthermore, damping of the CBR and B1 + mode is increased by the shaker. The lowest mode (B0) is not detected when the speaker is used in clamped-neck condition. As the B0 mode is associated

with a bending between the body and neck of the instrument, this could be attributed to the combination of the lower input energy of this excitation method and the additional damping caused by the clamp that holds the instrument at the neck position. Additionally, the speaker method resulted in higher frequencies for CBR and B1+, for which we cannot provide a clear reason. Because of this, the measurement was repeated in free-free condition for both speaker excitation and impact hammer (Table 4). Taking into account that our measurements have a resolution of 1 Hz, the obtained results from impact hammer (free-free) and speaker excitation (free-free) are identical in frequency, but show a small difference in damping values. Damping has been shown to be non-linear for different input energy levels [27]. However, the obtained damping values of impact hammer (free-free) and speaker excitation (free-free) do show similar trends between the modes. This could indicate that in the amplitude range used between these two methods, this nonlinear effect plays only a minor role.

Piezo and shaker excitation both contain significant errors as excitation methods, making them unreliable for modal analyses of violins. Of the two remaining excitation methods, impact hammer excitation provides the benefit of a known input signal. It introduces more energy in the system, which in turn provides a bigger amplitude in the measured response. The excitation however, is done locally by hitting the instrument at a predetermined location. This includes a risk of damage to the instrument, which is unacceptable in the case of historical instruments. Additionally, between each hit, the hammer operator must wait until the violin has completely stopped moving, especially in free-free setup, making the experiment very tedious and time consuming (approximately 2 h). As evident from our experience, the impact hammer method also requires a certain skill level of the operator in order to provide proper impact hits. Indeed, double hits should be avoided at all time, while also the induced energy should be kept as similar as possible since the induced energy could influence the extracted damping characteristics (in case of damping

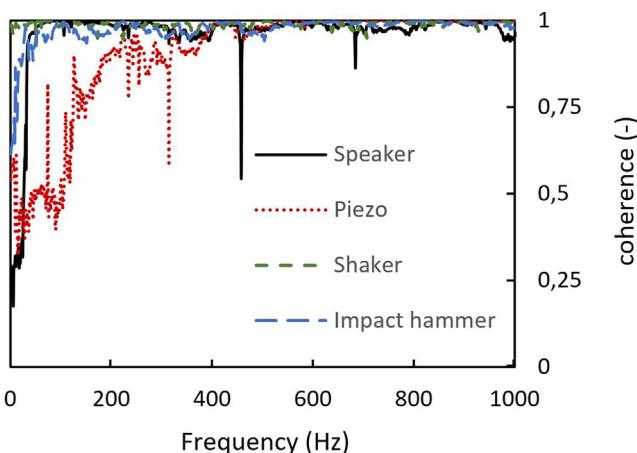


Fig. 6. Excitation methods. Average coherence for speaker, piezo, shaker and impact hammer excitation. Acquisition through SLDV.

Table 3

Excitation methods in clamped-neck condition. Signature modes, frequency (Hz) and damping (%) of different excitation methods in clamped-neck condition. Response was measured with the SLDV.

	Imp. Hammer	Speaker	Piezo	Shaker
B0	Freq.(damping) 223(0.8)	Freq.(damping)	Freq.(damping)	Freq.(damping) 223(0.08)
A0	247(1.63)	251(1.66)	249(0.6)	247(1.35)
A1	408(1.05)	408(0.87)	407(1.02)	441(0.96)
B1-	432(1.46)	434(1.4)		503(1.24)
CBR	453(0.49)	550(0.39)	540(0.87)	540(0.83)
B1+	550(0.6)	589(1.05)	579(1.18)	570(1.76)

Table 4

Excitation methods in free-free condition. Signature modes, frequency (Hz) and damping (%) of impact hammer and speaker excitation methods in free-free condition. Response was measured with the SLDV.

	Imp. Hammer	Speaker
B0	Freq.(damping) 225(0.47)	Freq.(damping) 225(0.84)
A0	249(2.03)	249(3.01)
A1	407(1.1)	407(1.07)
B1-	431(2.19)	431(2.31)
CBR	454(0.5)	461(0.18)
B1+	570(0.57)	569(0.71)

non-linearity). Of course, the latter concern could be removed by performing the experiment with an automated impact hammer [36], or by using a plastic handle in combination with an articulated arm on a stand. Excitation with a roving impact hammer can be combined with acquisition through a LDV or accelerometer on a fixed point. This makes it a less expensive method suitable for the workshop research practice. In comparison, speaker excitation requires acquisition at multiple measurement points. Therefore a more expensive scanning LDV (SLDV) is required. Even though the exact input energy of acoustic speaker excitation is unknown, the input signal sent to the speaker is sufficient to make an accurate modal analysis. This is evident from the high correlation between the results of the impact hammer (free-free) and speaker (free-free) experiment. Especially the non-contact excitation is beneficial as it distributes the input force over a larger surface area of the instrument as a pressure, which makes it the safest of the examined excitation methods. The method of speaker excitation meets all our predetermined criteria. As a result of this, acoustic excitation is a suitable excitation method to perform modal analyses on historical instruments. The reliability of this measurement method can likely be further improved even more: all experiments were conducted in a laboratory environment which was not free of noise, vibrations and acoustic reflections. It is feasible that when this experiment is performed in an anechoic chamber, the signal-to-noise ratio and reliability of the measurement is increased. Other possibilities are increasing the output of the speaker or increasing the number of averages per measurement point. When raising the amplitude of the speaker by a large amount, the safety of the researcher becomes a concern due to possible hearing impairment. Increasing the amount of averages per measuring point is likely to be the safest and easiest way to improve the coherence function, but it does not eliminate the effect of acoustic reflections.

3.3. Boundary conditions

The boundary or clamping conditions can restrict the vibrations of the component. When different mounting methods for speaker excitation are compared, a free-free condition shows the best coherence function (Fig. 7). The free-free condition is also the only

one that allowed all signature modes to be identified (Table 5) and has more similar results for CBR and B1 + in comparison to the impact measurement of Table 3. As mentioned previously, the B0 mode could not be identified in the clamped-neck condition. This is attributed to the fact that the B0 mode has a large amplitude in the neck at the position of the clamp. The violin stand had the lowest average coherence and the B0, CBR and B1 + modes were not found using PolyMAX.

To verify that the free-free condition is the preferred boundary condition, additional experiments were conducted with an impact hammer in free-free, clamped-neck and violin stand condition with SLDV acquisition (Fig. 8). Clamped-neck and violin stand provide a significantly better coherence function below 500 Hz. This could be caused by (1) human error: it is much harder for the hammer operator to get a 'good hit' on a violin in free-free condition due to the swinging motion of the violin, or (2) by laser drop-outs due to the same motion. The low coherence function of the free-free bound-

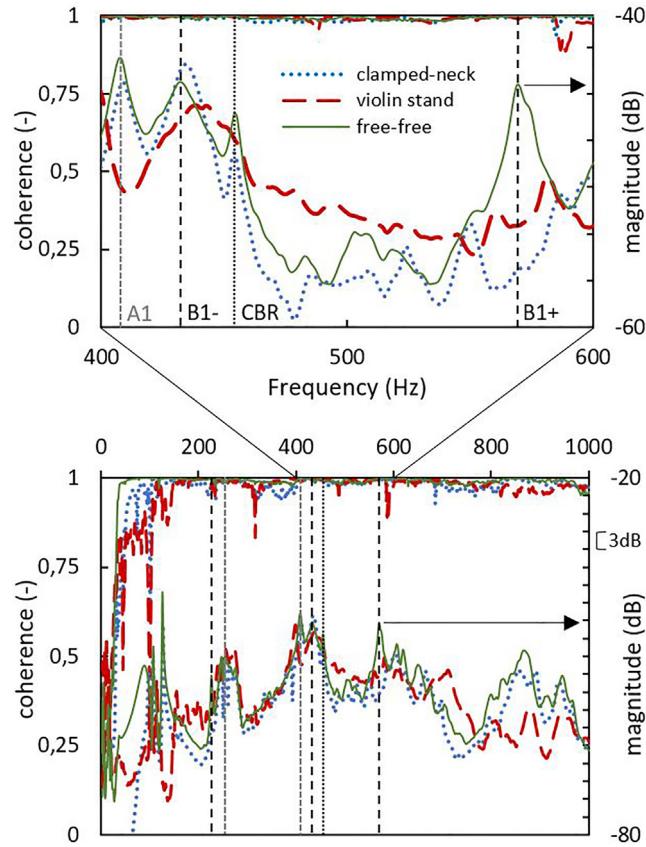


Fig. 7. Influence of boundary conditions on speaker excitation. Average coherence function and FRF in three boundary conditions for speaker excitation. Free-free condition (black) has the best coherence, followed by clamped by neck (dark gray, dotted line). Violin stand (light gray, dashed line) has the lowest average coherence.

Table 5

Boundary conditions. Signature modes, frequency (Hz) and damping (%) obtained by speaker excitation in different clamping conditions.

	free-free	clamped-neck	violin stand
B0	Freq. (damping) 225 (0.84)	Freq. (damping)	Freq. (damping)
A0	249 (3.01)	251 (1.66)	253 (2.48)
A1	407 (1.07)	408 (0.87)	398 (1.13)
B1-	431 (2.31)	434 (1.4)	439 (2.75)
CBR	461 (0.18)	550 (0.39)	
B1+	569 (0.71)	589 (1.05)	

ary condition for impact hammer can have an effect on the damping extraction. Our obtained damping values show a similar trend as speaker excitation (free-free), which would indicate this effect to be limited in this experiment. When the results of the modal analysis are compared, the B1 + mode shifts 20 Hz upwards in the clamped-neck condition and 12 Hz downwards in the violin stand condition compared to free-free. As all boundary conditions have an average coherence above 0.9 at these frequencies, this shift is most likely caused by the change in boundary conditions. In the violin stand condition the CBR mode could not be identified. The FRF function also depicts additional peaks introduced by the clamped-neck condition. As such, a free-free condition is preferred.

4. Recommendation for workshop and laboratory practice

Laboratory practice: When more expensive equipment is available, acoustic speaker excitation in combination with a scanning laser Doppler vibrometer to measure the response signal in a free-free boundary condition provides a safe and reliable method to identify the signature modes of a violin (Table 6).

Workshop research practice: When minimal damage like surface dents are less of a concern, but the cost of equipment must be limited, roving impact hammer excitation with a lightweight accelerometer provides a good solution. However, the effect of the added mass of the accelerometer must be taken into account when assessing the results. Impact hammer excitation in combination with a laser Doppler vibrometer provides a better, but more expensive solution (Table 6). The reliability of modal analysis with impact hammer excitation is dependent on the skill of the operator; it is crucial this is taken into consideration when assessing results obtained through this method.

5. Validation of the non-contact method

To validate whether the recommendation for laboratory practice is suitable for application on more fragile instruments, a contemporary wooden violin (2012) was investigated. The contemporary violin has been manufactured based on one of the most well-known historical violins, the Stradivari 'Messiah' violin (1716) [1]. Table 7 shows the results of the modal analysis for this violin compared to literature values of other wooden violins [4,24,30]. Fig. 9 depicts the FRF function and average coherence function. The frequencies of the signature modes fall between the values obtained by Bissinger [4] on 17 wooden violins through impact hammer excitation. The values from Skrodzka et al. [30] are significantly higher in both frequency and damping, this can be attributed to the boundary condition used in this experiment (clamped by the sides) which is likely to have changed the modal behaviour of the examined violin significantly. This variation in results is another indication that the experimental set-up can have a large influence on the results of the measurement. If we wish to compare between instruments, they must be measured in the same experimental condition.

The damping values obtained through PolyMAX show trends for the wooden and carbon violin. A0 has the highest damping (1.8 & 3.01), followed by B1- (1.13 & 2.31), A1 (1.00 & 1.07) and B1+ (1.00 & 0.71). B0 (0.76 & 0.84) and CBR (0.78 & 0.43), have low damping in both violins. Our proposed non-contact method allows the investigation of the damping of the signature modes. The damping value of modes could be an important parameter to understand the link between the vibrational behaviour and the radiated sound of an instrument. The damping of a mode contains both the structural and radiational dissipation of energy. In cases where the structural losses of a mode can be considered a constant, for example between two instruments that are made to be identical, a higher damping value can be an indication that a mode dissipates vibrational energy effectively due to acoustic radiation. In violins this is likely beneficial as it would make this mode an efficient sound radiator. The average coherence function for the wooden violin measurement is lower than the carbon violin. This is caused by the different surface finish of the instruments. The carbon violin has a matt finish which results in a superior SLDV signal quality compared to the glossy surface finish of the wooden instrument. Additionally, a surprising drop in the coherence function is observed at the B1 + mode for the wooden violin. Possibly this is due to some non-linear phenomenon within the instrument such as rattle.

6. Conclusion

In this paper our goal was to develop a reliable no-risk method to perform modal analyses on fragile music instruments. First an overview of the existing literature on the influence of different acquisition methods, excitation methods and boundary conditions on the modal analysis of a violin has been given. Then we focused on a number of different approaches to modal analysis. The most suitable method is determined by the context of the measurement, therefore two practices can be distinguished: (1) the workshop research practice of an instrument maker, which must be reliable but operational at a relatively low cost. (2) The laboratory practice of a scientist, with its strong emphasis on both reliability and the preservation of the instrument. A carbon violin was used as a first case study to compare between experimental modal analysis methods. In order to make sure the proposed laboratory practice was suitable for use on for example historical instruments, this method was also applied on a fragile wooden violin.

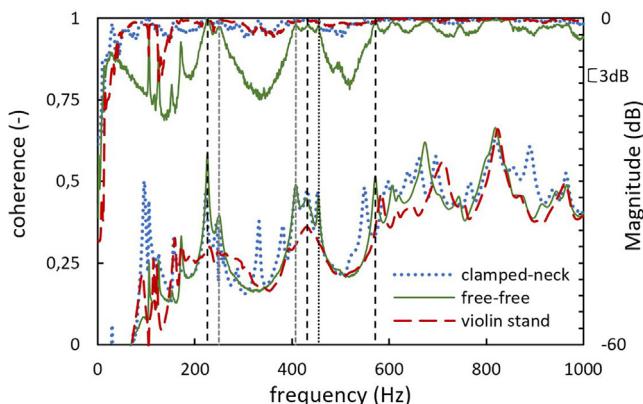


Fig. 8. Influence of boundary conditions on impact hammer excitation. Average coherence function and FRF in three boundary conditions for impact excitation. Clamped neck and violin stand have a better coherence but cause shifts in the frequency of modes. Also clamped-neck introduces additional resonances not associated with the violin.

Table 6

Summary of the (dis-)advantages of different measurements methods. Speaker excitation and SLDV response are the safest, but most expensive method. Impact hammer provides a cheaper alternative but includes a small risk of damage. In the case a lightweight accelerometer is used to measure the response, the effect of the added mass on the vibration response must be considered.

Recommendation	Exc.	Acq.	Boundary	Suitable for modal analysis	added mass	risk of damage	Cost
Laboratory	Speaker	SLDV	free-free	yes	no	no	high
Workshop	Imp. hammer	LDV	free-free	yes	no	yes	mod.
Workshop	Imp. hammer	Acc.	free-free	yes	yes	yes	low

Table 7

Validation of the laboratory practice. Signature modes, frequency (Hz) and damping (%) obtained through acoustic speaker excitation in free-free condition in comparison to values obtained by Bissinger on 17 wooden violins through impact hammer excitation, Pyrkosz and Van Karsen on one violin and Skrodzka et al. on one violin with 3 different bass bar tensions.

	Contemp. wooden violin	Bissinger [4]	Pyrkosz and Van Karsen [24]	Skrodzka et al. [30]
B0	Freq. (damping) 255 (0.76)	Freq.	Freq. (damping) 238 (0.57)	Freq. (damping)
A0	268 (1.80)	253–282	292 (2.27)	297–337 (8.0–8.2)
A1	486 (1.00)	430–494	503 (1.35)	
B1-	455 (1.13)	439–500	538 (1.61)	586–592 (3.0–5.9)
CBR	427 (0.78)	363–452	433 (1.40)	483–485 (2.3–2.6)
B1+	549 (1.00)	511–591	560 (1.06)	671–687 (4.3–5.0)

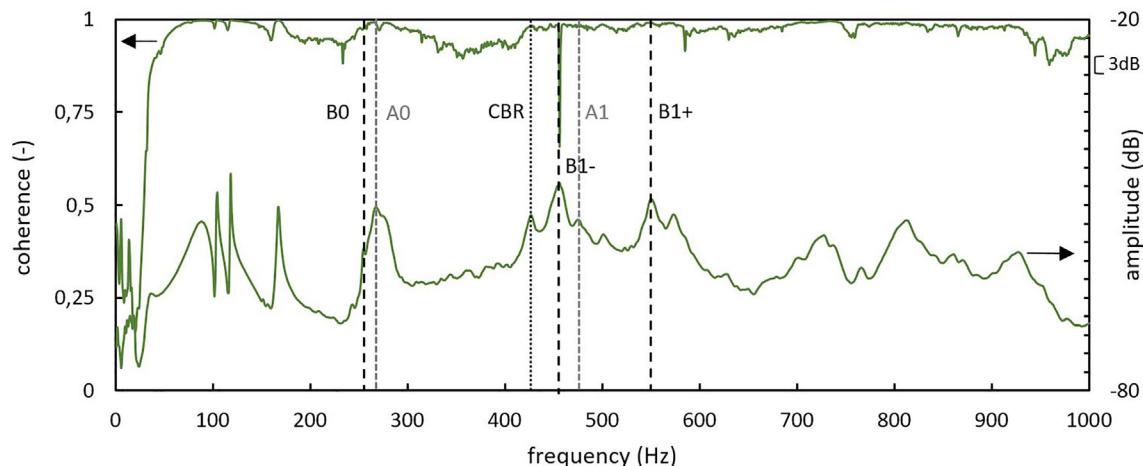


Fig. 9. Validation of the laboratory practice. Average coherence function, FRF and indication of signature modes for the wooden violin measured using speaker excitation and SLDV in free-free conditions.

Both a lightweight accelerometer and laser Doppler vibrometer (LDV) can be used for acquisition purposes. In the case of the accelerometer however, the mass-loading effect of the method must be taken into account and the lowest possible mass for the accelerometer is recommended. Acquisition through a LDV is more expensive but non-contact, and is thus preferred in a laboratory environment.

Four excitation methods for experimental modal analysis of violins were compared: (1) miniature impact hammer, the current standard for experimental modal analysis on violins, (2) electromagnetic shaker, (3) piezo elements and (4) acoustic excitation through a speaker. The results obtained with an electromagnetic shaker and piezo elements were deemed unsuitable for the investigated application as the results did not meet our criteria. Both impact hammer excitation and speaker excitation resulted in reliable measurements allowing the identification of the signature modes (B0, A0, A1, B1-, CBR and B1+) and their modal parameters, i.e. frequency (Hz) and damping (%). Excitation through impact hammer can lead to a lower reliability when it is difficult to consistently achieve 'good' hits. In the presented modal experiments, this is the case when the violin was in a free-free condition. Additionally, hitting an instrument with an impact hammer includes a risk

of damage, which is unacceptable in the case of fragile violins. Acoustic excitation through a speaker provides a faster, safer and reliable alternative for experimental modal analysis, and is therefore recommended for laboratory practice. This method requires acquisition through a scanning laser Doppler vibrometer (SLDV), which makes it too expensive for use in the violinmakers workshop research practice.

As can be expected, boundary conditions have a significant influence on the modal analysis of a violin and can even prevent signature modes from being identified. In order to be able to compare modal parameters of different instruments, a free-free condition is recommended.

Of course, this measurement method has its limitations. The laboratory practice provides qualitative, but not quantitative data. If we want to deepen our understanding on the link between the vibrational behavior of a violin and its playability and sound, we must combine it with other experiments. However, using the low-risk non-contact method proposed for laboratory practice, the vibrational behavior of instruments previously deemed too fragile for experimental modal analysis with an impact hammer can be studied. Hopefully, by using the proposed method, researchers can convince owners or curator of unique and valuable music

instruments to lend these interesting objects to research. Only by using safe non-contact and reproducible methods, we can learn more about these fascinating objects without compromising on their preservation.

CRediT authorship contribution statement

Tim Duerinck: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Resources, Writing - original draft, Funding acquisition. **Joost Segers:** Methodology, Investigation. **Ewa Skrodzka:** . **Geerten Verberkmoes:** Conceptualization, Methodology, Supervision, Funding acquisition. **Marc Leman:** Conceptualization, Supervision. **Wim Van Paepgem:** Conceptualization, Methodology, Resources, Supervision, Funding acquisition. **Mathias Kersmans:** Conceptualization, Methodology, Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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