

The acoustic role of rosette design in the oud: An experimental study of geometric and mechanical effects

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Abstract

Oud rosettes have traditionally been discussed primarily as decorative structures covering the sound holes, although their acoustic and mechanical roles remain insufficiently resolved. This study investigates rosette design within a unified vibroacoustic framework. The geometric analysis considers total open area, regional open-area distribution, and total aperture-edge length, whereas the mechanical analysis considers progressive added mass and connectivity/stiffness-proxy configurations. A single fully playable oud and a set of interchangeable experimental rosettes were used to isolate local design changes from inter-instrument variability. For each configuration, the structural response was characterized through bridge-mobility measurements, and the force-normalized acoustic response was measured with a calibrated microphone positioned 1 m from the instrument under standardized conditions. The lightweight geometry series produced comparatively modest, descriptor-specific changes; the clearest openness effects occurred at the fully Closed and Open boundary conditions. Progressive added mass produced the most regular downward shift and reduction of the bridge-mobility peak around 220 Hz, whereas the connectivity/stiffness-proxy series evolved non-monotonically and was dominated by the F4 departure. In the experimental oud examined here, the findings support treating the rosette as a coupled geometric and mechanically interacting component rather than as a decorative cover or an open-area descriptor alone.

Keywords

oud acoustics, rosette geometry, aperture-edge length, added mass, structural connectivity, bridge mobility, force-normalized acoustic response

Introduction

Sound holes provide the principal acoustic connection between the enclosed air volume of a string instrument and the surrounding medium (Elejabarrieta et al., 2002; Nia et al., 2015). In some instruments, including the classical guitar, the opening is unobstructed; in lute-family instruments such as the oud, it may be covered by an intricate lattice known as a rosette (Tavakoli Nia, 2010). The rosette consequently forms part of the opening through which the internal pressure field couples to the exterior. More broadly, audible sound results from the interaction of the strings, bridge, soundboard, body, and enclosed air rather than from any component acting in isolation (Firth, 1977).

The oud is a short-necked, fretless, pear-shaped lute with a long history in the musical traditions of Türkiye and the wider Eastern Mediterranean and

Middle East. Its construction has varied over time, including changes in the number, placement, and geometry of its sound holes (Güler, 2022). Contemporary instruments may employ one or several openings, but a large central sound hole flanked by two smaller openings remains a characteristic arrangement. The rosettes that cover these openings also carry substantial visual and craft significance: their lattice patterns, workmanship, and ornamentation can identify individual makers and construction traditions (Arslan & Alaskan, 2022; Güler, 2022). Historical comparison of a seventeenth-century lute attributed to Istanbul likewise treats rosette geometry as a diagnostic feature of making tradition (Güler, 2025). Against this craft-historical background, contemporary luthiery increasingly combines traditional craft knowledge with digital modeling, acoustic simulation, and parametric, research-based design methods, using

technological tools to extend rather than replace craftsmanship (Turan, 2025).

This geometric diversity has acoustic implications that cannot be reduced to the amount of open area alone. Work on violin-family sound holes has shown that acoustic conductance is strongly governed by flow near the aperture perimeter and that elongated openings can increase edge length without a corresponding increase in void area (Nia et al., 2015). Tavakoli Nia (2010) similarly demonstrated that conventional estimates based mainly on total void area can substantially misrepresent the air-resonance behavior of complex lute rosettes. Total open area, the spatial distribution of openings, and aperture-edge length must therefore be treated as related but non-equivalent geometric descriptors.

The acoustic role of a sound hole is commonly associated with the low-frequency Helmholtz-type air resonance. Its function, however, is not confined to that resonance. At wavelengths large relative to the instrument, opposing regions of a vibrating soundboard can radiate inefficiently because of phase cancellation. The same structural motion can produce time-varying volume changes within the cavity, excite the internal pressure field, and create an additional radiation path through the sound hole (Bissinger et al., 2007; Firth, 1977). Sound-hole and rosette effects must thus be interpreted within the coupled response of the soundboard and enclosed air.

A rosette is also a physical component with finite mass and structural stiffness. When attached to the soundboard, it can modify the local distribution of inertia and stiffness around the sound-hole region as well as the geometry of the air passage. Studies of structural additions to guitar soundboards show that changes in the mass and stiffness of an attached element can alter the natural frequencies of the combined system (Dumond & Baddour, 2012). Although a soundboard brace and an oud rosette serve different structural functions, this evidence

provides a physical rationale for treating the rosette as both an aperture-forming element and a mechanically coupled component.

Research on complex sound holes has nevertheless concentrated mainly on local acoustic behavior. Tavakoli Nia (2010) compared rosette configurations using a microphone inside a test cavity and focused on air-resonance frequency and bandwidth. Bader (2012) examined vihuelas and a classical guitar with a microphone array positioned only 3 cm from the instruments, whereas the contribution of violin f-holes has been estimated from near-field measurements and numerical projection (Bissinger et al., 2007). These approaches provide important information about local pressure and aperture radiation. The present study complements this work by comparing the force-normalized acoustic responses of interchangeable oud rosettes at 1 m using a fixed instrument-microphone geometry.

The present study addresses this gap by examining experimentally interchangeable oud rosettes at a distance of 1 m. It combines three geometric variables (total open area, regional open-area distribution, and total aperture-edge length) with two mechanical comparison series (progressive added mass and connectivity/stiffness-proxy configuration) within the same controlled framework. The central research question is:

- How do changes in the geometric and mechanical properties of oud rosettes affect the instrument's vibroacoustic response and force-normalized acoustic response at 1 m?

The Oud as a Vibro-Acoustic System

The oud can be described as a coupled vibroacoustic system in which string energy is transmitted through the bridge to the soundboard, while soundboard motion simultaneously drives the enclosed air. Its relatively deep bowl, thin soundboard, and multiple sound holes create an acoustic configuration in which structural modes,

cavity modes, and radiation through the openings interact strongly (Değirmenli, 2018). The rosettes lie directly within this coupling path: they shape the openings through which air moves and, because they are attached to the soundboard, may also modify the local mechanical response.

Figure 1 identifies the principal components relevant to this interaction. Recent oud-specific vibroacoustic research has similarly shown that changes in soundboard bracing geometry can alter modal frequencies and acoustic radiation characteristics (Abdallah et al., 2026).

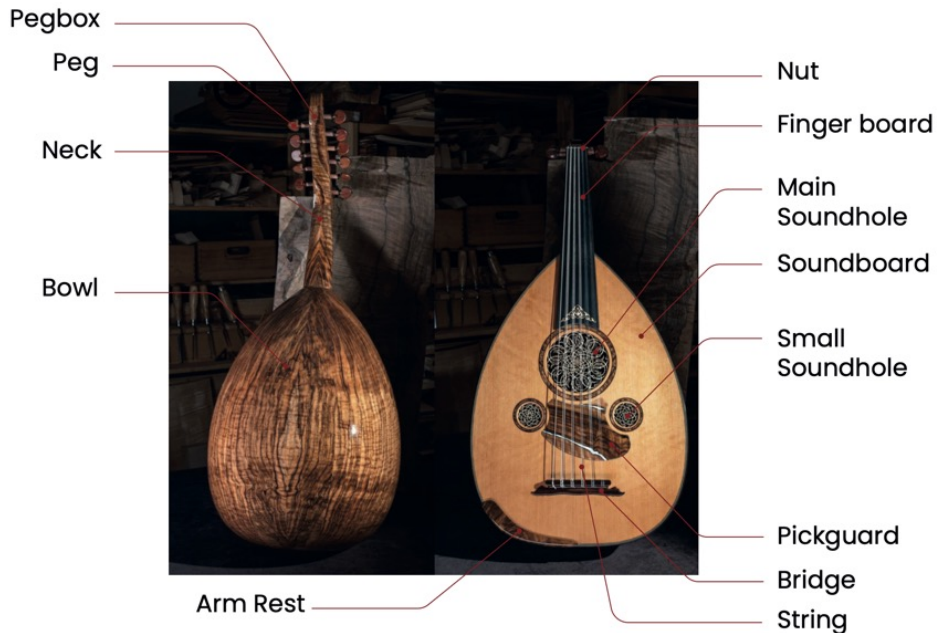


Figure 1. Principal parts of the oud

Sound Production and Structural Modes in the Oud

At low frequencies, the soundboard response is dominated by a limited set of normal modes. Each mode has a characteristic natural frequency and spatial displacement pattern defined by nodal and antinodal regions (Fletcher & Rossing, 1998). Because the bridge transfers string force to the plate, the relationship between bridge position and modal shape affects both the mobility measured at the bridge and the efficiency with which vibrational energy is radiated. Comparable work on another plucked string instrument has used bridge driving-point response and low-frequency modal behavior to examine the coupling between string excitation and body vibration (Tufte et al., 2019).

The oud soundboard is coupled to a large, deep bowl and supports a broad region around the central sound hole. These features make local modifications near the opening potentially relevant to the low-frequency response, but they do not justify treating the rosette as an independent radiator. Any rosette-related effect must be evaluated as a perturbation of the complete instrument, whose response depends on the soundboard, bowl, enclosed air, bridge, and boundary conditions (Değirmenli, 2018).

From a structural perspective, adding or removing material near an antinodal region changes the local balance between inertia and stiffness, whereas a modification near a nodal region may have a smaller modal effect. Consequently, rosettes with similar aperture geometry need not be

mechanically equivalent if their masses or structural stiffnesses differ. Conversely, mechanically similar rosettes can present different acoustic boundary conditions when their openings are distributed differently. This distinction motivates the two-part experimental design adopted here.

Enclosed Air Modes and Helmholtz Resonance

In addition to structural modes, the oud supports acoustic modes of the enclosed cavity. The lowest is the Helmholtz-type A0 resonance, produced by oscillatory airflow through the sound holes in response to pressure fluctuations within the body (Fletcher & Rossing, 1998). Its frequency and bandwidth depend on the cavity volume and on the effective acoustic mass and conductance of the openings; they therefore depend on more than the nominal diameter or total area of the sound holes.

For complex apertures, flow is concentrated near the edges, and the effective behavior of the opening depends on edge length, thickness, and the interaction among individual perforations (Nia et al., 2015; Tavakoli Nia, 2010). In a multi-hole instrument such as the oud, regional distribution may additionally affect how the aperture field couples to local cavity pressure and soundboard motion. Accordingly, total open area, regional distribution, and aperture-edge length are treated separately in the present study rather than being collapsed into a single openness measure.

Structural-Acoustic Coupling

Structural-acoustic coupling is bidirectional: soundboard motion changes the cavity volume and pressure, while the internal pressure field exerts force on the soundboard. This interaction can shift coupled resonance frequencies, modify damping, and redistribute radiation between the soundboard and the apertures (Elejabarrieta et al., 2002; Fletcher & Rossing, 1998).

At low frequencies, structural motion that radiates weakly into the exterior can still excite the cavity efficiently. The resulting internal pressure then radiates through the sound holes, providing a pathway additional to direct soundboard radiation (Bissinger et al., 2007; Firth, 1977). This mechanism is especially relevant when interpreting measurements near the A0 resonance and when comparing mobility with sound-pressure response. Previous musical-acoustics research has likewise shown that structural vibration and radiated sound need not exhibit a one-to-one correspondence, because radiation efficiency depends on both modal motion and the spatial distribution of radiating regions (Wang & Burroughs, 1999).

Within this coupled system, rosette geometry affects the acoustic boundary presented by the sound hole, whereas rosette mass and structural stiffness affect its mechanical interaction with the surrounding soundboard. These mechanisms may coexist and cannot be inferred reliably from material labels or open-area ratio alone. Figure 2 illustrates the relation between measured response features and representative oud vibration patterns.

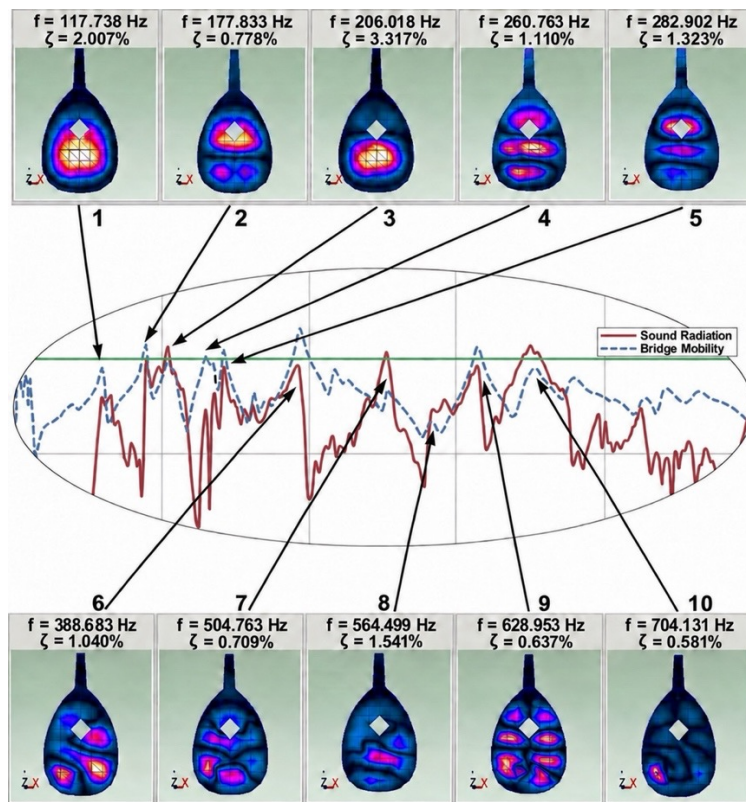


Figure 2. Representative vibration modes of the oud soundboard and the corresponding sound-radiation and bridge-mobility responses. The natural frequency (f) and damping ratio (ζ) are indicated for each mode (Değirmenli, 2018)

Literature Review

Studies of guitar and violin acoustics have established the importance of sound holes in low-frequency cavity response and radiation (Bissinger et al., 2007; Elejabarrieta et al., 2002; Firth, 1977). Research on violin-family apertures further shows that aperture perimeter, rather than area alone, governs acoustic conductance for thin sound-hole geometries and helps explain the historical development of elongated f-holes (Nia et al., 2015). These findings provide an essential geometric framework but do not fully describe a densely perforated rosette attached to a flexible oud soundboard.

The most directly relevant rosette study is Tavakoli Nia's (2010) theoretical and experimental analysis of lute roses and other complex sound holes. That work demonstrated the limitations of total-void-area approximations and emphasized near-

edge flow, but its experimental comparisons focused on cavity resonance and used a microphone inside a test box. Bader's (2012) measurements of vihuelas and a classical guitar were obtained in the near field, approximately 3 cm from the instruments. The present study extends these comparisons to interchangeable rosettes on a playable oud, using bridge mobility and force-normalized acoustic response measured at 1 m with a fixed microphone position relative to the instrument.

A second limitation concerns mechanical characterization. Existing rosette comparisons have generally treated the pattern as an acoustic opening, without isolating the rosette's mass and structural stiffness as experimental variables. Related soundboard research confirms that the mass-stiffness balance of attached structural elements can affect natural frequencies

(Dumond & Baddour, 2012), but this principle has not been tested systematically for oud rosettes. Oud studies have instead concentrated on global body-air interaction and the modal and radiation behavior of complete instruments (Değirmenli, 2018). The separate and combined contributions of rosette geometry and mechanical properties therefore remain insufficiently resolved.

Research Problem

The research problem arises from a mismatch between the physical complexity of the rosette and the variables used to describe it. A rosette is simultaneously a perforated acoustic boundary and a mechanically coupled addition to the soundboard. Comparisons based only on total open area can confound openings with different spatial distributions and edge lengths, while comparisons based only on material or thickness can confound mass, stiffness, and geometry.

The present study addresses these limitations through two complementary parameter groups. The geometric group comprises total open area, regional open-area distribution, and total aperture-edge length. The mechanical group comprises progressive added mass and connectivity/stiffness-proxy configurations. Interchangeable rosettes are tested on the same playable oud, and their effects are evaluated through bridge mobility and force-normalized acoustic response measured at 1 m. This framework permits the local role of the rosette to be examined without attributing differences to variation among instruments.

Accordingly, the aim is to determine how geometric and mechanical variations in oud rosettes relate to the instrument's vibroacoustic response and radiated sound. The study does not presume that any one descriptor will dominate; rather, it tests whether the observed response requires an explanation based on aperture geometry, structural properties, or their coupled influence.

Method

Research Model

This study employed a controlled within-instrument repeated-condition design in which interchangeable rosettes were tested sequentially on the same fully playable oud. The experimental unit was the single instrument, and repeated analyzer averages were used to improve measurement stability rather than as independent experimental replicates. The design separates two complementary variable families: (i) the geometric-acoustic descriptors of total open area, regional open-area distribution, and total aperture-edge length; and (ii) the mechanical comparison variables of progressive added mass and connectivity/stiffness-proxy configuration. Instrument setup, excitation, sensor placement, microphone position, and environmental conditions were held constant across configurations. Bridge mobility and the force-normalized acoustic response at 1 m were measured for each rosette, providing paired frequency-dependent responses for within-instrument comparison.

Experimental Instrument

The measurements were conducted on a single fully playable oud (Photo 1). This choice was made to avoid the constructional and material variability inherent in comparisons among handmade instruments and to preserve a fixed structural baseline for all rosette conditions. The experimental logic therefore concerns the response of one instrument to controlled local changes rather than population-level differences among ouds.



Photo 1. Experimental oud and measurement setup: (a) impact-hammer excitation applied to the bridge via an extension arm; (b) oud mounted in the experimental fixture (Author's personal archive).

A single-instrument design is appropriate for detecting small response changes caused by interchangeable components, provided that the intervention and measurement sequence are repeatable. It does not, however, establish the magnitude of the same effects in instruments with different soundboards, bowls, bracing systems, or sound-hole arrangements. That distinction is retained in the interpretation and limitations of the study.

String type, tuning, bridge position, instrument support, and sensor and microphone locations were kept unchanged throughout the measurement sequence. No structural intervention other than substitution of the experimental rosette was introduced between trials.

Design and Fabrication of Interchangeable Rosettes

The interchangeable rosettes were organized into geometric and mechanical comparison sets. The geometric set was designed to vary total open area, the regional distribution of that area, and total aperture-edge length. These descriptors were recorded separately because rosettes with similar total open area can differ substantially in the number, placement, and perimeter of their individual apertures. The equal-area analysis framework and design-specific configurations are documented in Supplementary Figures S1-S8. The principal geometric and mechanical values defining the experimental series are summarized in Table 1; complete condition-level values are provided in Supplementary Tables S3-S7.

Table 1. Principal values defining the controlled rosette series

Series	Conditions	Open-area ratio	Aperture-edge length	Mass or proxy
Total openness	A1-G-A4-G (fixed-perimeter subset); Closed/Open (boundary references)	37.367-57.804% for A1-G-A4-G; 0/100% boundaries	A1-G-A4-G: fixed within each size—1,401.411 mm (large); 626.759 mm (small)	Theoretical PMMA: 9.226-13.661 g large; 1.941-2.881 g small
Regional distribution	T1-T3	18.00%; regional ratios 30/12/12, 12/30/12, 12/12/30%	788.610 mm large; 362.120 mm small	Theoretical PMMA: 17.886 g large; 3.771 g small
Aperture-edge length	K1-G-K4-G	49.1386%	1,147.905-1,651.905 mm large; 512.702-738.602 mm small	Theoretical PMMA: 11.094 g large; 2.339 g small
Added mass	M0, M3, M6, M9 on fixed K2-G set	49.1386%	Set total: 2,491.910 mm	Added mass: 0, +3, +6, +9 g; theoretical PMMA set mass: 15.772 g
Connectivity/stiffness proxy	F1-F4	47.5600%	1,240.259-1,736.450 mm large; 569.507-797.350 mm small	Theoretical PMMA: 14.507 g large; 3.875 g small; relative proxy normalized to F1 = 1

The rosette geometries were generated parametrically from researcher-defined dimensions and comparison constraints. OpenAI gpt-5.6-sol, accessed through Codex, was used as an AI-assisted design tool to support implementation and iteration of the parameterized geometries; the researcher retained responsibility for selecting variables, defining constraints and comparison sets, and accepting the final designs, and the system was not used to produce experimental results or interpret the measured responses. The geometries were then imported into Autodesk Fusion 360 for dimensional and geometric verification before specimen preparation. Checks covered the standardized outer and active diameters, total and regional open-area ratios, solid area, aperture distribution, and total aperture-edge length documented in Supplementary Figures S1-S8 and Tables S1-S7; parameters designated as controls in each comparison set were verified against the corresponding design specifications.

For the geometric comparisons, the rosettes were fabricated from 2.0-mm AIREX® C70.75 closed-cell PVC foam with controlled external dimensions and mounting conditions. This lightweight material was selected to limit additional inertial loading while the aperture pattern was varied. Differences in the installed mass of the intermediate geometric configurations remained well below 1 g; within the A1-G-A4-G total-openness subset, the variation across the complete sequence was approximately 0.3 g, with approximately 0.1 g between adjacent openness levels. Nevertheless, the specimens were not assumed to be mechanically identical, and possible differences in mass and stiffness were retained as limitations of the geometric comparisons.

Two boundary conditions were also defined for reference measurements. In the Open condition, all three sound holes were left unobstructed, and no rosettes or inserts were installed. In the Closed condition, one large and two small inserts made from

the same 2.0-mm AIREX® C70.75 foam were gently compression-fitted into the three sound-hole openings. The combined measured mass of the three closure inserts was approximately 1.4 g. The Closed condition therefore introduced both a small added mass and a compression-contact constraint relative to the Open condition and was treated as an operational boundary reference rather than as a mechanically identical counterpart differing only in open area. The interchangeable rosettes used in the remaining conditions were positioned consistently and secured with tape, as described below.

The mechanical comparison comprised (i) a progressive added-mass series applied to a fixed K2-G rosette set and (ii) the F1-F4 connectivity/stiffness-proxy configurations. The specimens used in both the M- and F-series were fabricated from 3-mm-thick acrylic (PMMA) sheet. The measured mass of the three-rosette K2-G set was 15.8 g. In the added-mass series, M0, M3, M6, and M9

denoted 0, +3, +6, and +9 g added to this baseline rosette set, respectively. Mass was increased by adding nuts to the same K2-G rosette set in nominal steps of approximately 3 g. The nuts were positioned in the central regions of the small rosettes and at the other locations documented in Figure 3c and Supplementary Figure S7. Cyanoacrylate (CA) adhesive secured the nuts to minimize independent vibration, loosening, or displacement during measurement. The rosette geometry and configuration remained unchanged throughout the series. In F1-F4, total and regional open-area ratios and solid area were held constant, whereas connection topology and the geometry-only proxy varied; total aperture-edge length also co-varied within this series and was therefore retained as a disclosed geometric covariate. The proxy was not a measured physical stiffness in N/m (Figure 3; Supplementary Figures S7-S8 and Tables S6-S7). Accordingly, the F1-F4 series should not be interpreted as a linear or readily predictable one-factor stiffness-proxy response.

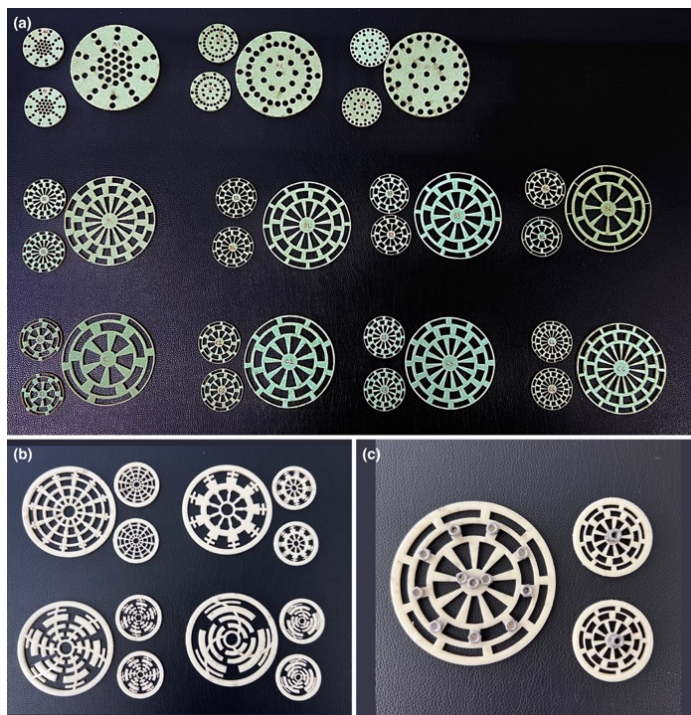


Figure 3. Experimental rosette sets: (a) lightweight foam specimens for geometric comparisons, (b) specimens used for the connectivity/stiffness-proxy series, and (c) specimens used for the added-mass series

All specimens were produced for repeatable installation in the same sound-hole locations. The mounting interface was kept as consistent as practicable to minimize changes in contact and boundary conditions. A limited remove-and-reinstall repeatability check was performed for the A4-G configuration. Across the 50-2000 Hz analysis range, the bridge-response magnitude spectra obtained before and after remounting were highly correlated ($r = 0.998$), with a median absolute difference of 0.25 dB; the matched prominent structural peaks generally differed by no more than 3.1 Hz. The corresponding sound-radiation spectra also retained a similar overall response shape ($r = 0.968$), although the median absolute magnitude difference was higher, at 0.89 dB. Because this check included only one configuration and one remove-and-reinstall cycle, it was treated as supporting evidence of short-term mounting repeatability rather than as a statistical characterization of mounting-related uncertainty. The two parameter sets together enabled geometric-acoustic and mechanical-structural effects to be considered within the same instrument and measurement framework.

The three rosettes comprising each experimental condition (one large and two small) were mounted simultaneously using 3M 468MP adhesive transfer tape. Because this transfer tape contains no foam or other thick compliant carrier, it was selected to provide a thin, minimally intrusive interface between the rosettes and the soundboard and to approximate the direct attachment of traditional rosettes.

Measurement Setup and Experimental Procedure

Measurements followed an impact-based vibroacoustic procedure consistent with experimental practice in string-instrument research (Schleske, 2002a). The measurement chain comprised a Brüel & Kjær Type 8204 miniature impact hammer, a Type 4517 miniature accelerometer, a Type

4189-A-021 1/2-inch free-field microphone set with Type 2671 preamplifier, and a six-channel Type 3050-A-060 data-acquisition module; Type 7781-N6 PULSE Access FRF Analysis software was used for acquisition and analysis. Each rosette configuration was evaluated using the same excitation and acquisition chain. The structural and acoustic responses were measured sequentially without altering the instrument support or rosette mounting. Complex H1 frequency-response functions were acquired in PULSE LabShop version 20.0.0.455 (2015-10-22 build) using FFT spectrum averaging. A uniform window was applied to the force, acceleration, and pressure channels. The exported spectra covered 0-10 kHz in 6401 frequency bins, including 0 Hz, with a frequency increment of $\Delta f = 1.5625$ Hz and a 0.64 s record length. The fixed instrument support, excitation, sensor, and microphone arrangement is shown in Figure 4.

Bridge response was obtained from controlled broadband impact excitation using an instrumented hammer, a vibration sensor mounted at the bridge, and a frequency-domain acquisition system. The raw complex mechanical FRF was accelerance, $H_a(f) = a(f)/F(f)$, in $\text{m s}^{-2} \text{N}^{-1}$. For publication, the raw accelerance files were preserved and bridge mobility was derived for $f > 0$ as $Y(f) = v(f)/F(f) = H_a(f)/(j2\pi f)$, in $\text{m s}^{-1} \text{N}^{-1}$.

The strings remained tuned to the instrument's standard tuning and were damped during all measurements to suppress string vibration while maintaining string tension. String damping was provided by six pieces of soft foam placed at separate contact points along the strings; their positions were selected to avoid the sound-hole regions and thereby minimize any influence of the damping material on the measured acoustic response. Hammer impacts were applied at the same bridge position and in the same direction for all trials. Each exported mechanical accelerance FRF contained five analyzer averages, whereas each acoustic pressure-to-force FRF contained 36 analyzer

averages. For the mechanical channel, the five averages comprised repeated impacts at the fixed bridge/sensor configuration. For the acoustic channel, measurements were acquired at successive 10° orientations of the instrument-microphone assembly over one complete revolution relative to the room. The microphone was positioned at a distance of 1 m from the soundboard surface, measured along the axis normal to the soundboard and passing through the midpoint between the centers of the two small sound holes. The oud and microphone were rotated together, with this distance and relative geometry maintained throughout the measurement sequence. Thus, the microphone sampled the same direction relative to the instrument at every platform orientation. This procedure was intended to reduce the influence of room reflections and resonances associated with a single orientation of the assembly, following

the room-averaging approach discussed by Curtin (2009). It did not sample different radiation directions around the instrument and was not assumed to eliminate room effects. The analyzer averages were not treated as independent reinstallation replicates.

Acoustic measurements were acquired in PULSE LabShop using Spectrum Averaging, with linear averaging and 36 averages. The analyzer averaged the force autospectrum and the complex force-pressure cross-spectrum over the 36 measurement records and calculated the acoustic H1 response from their ratio. The reported acoustic levels were calculated from the magnitude of this resulting complex response. Throughout the averaging sequence, the oud and microphone were rotated together relative to the room while maintaining their relative positions and orientation.

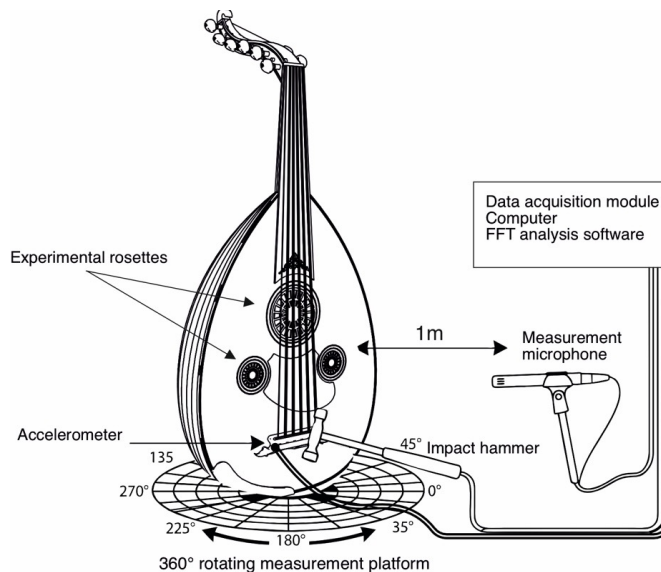


Figure 4. Experimental measurement setup. During acoustic acquisition, the oud and microphone were rotated together in 10° increments relative to the room, while their relative positions, microphone orientation, and 1 m separation remained fixed

The acoustic response was measured using a calibrated microphone positioned in front of the oud at a distance of 1 m. The acoustic channel was acquired using the H1 estimator as the complex force-normalized sound-pressure response $H_p(f) = p(f)/F(f)$, in Pa N^{-1} . The microphone position and orientation

relative to the oud, together with the gain settings, were maintained throughout the experiment. Measurements at successive room orientations therefore characterized the exterior sound-pressure response for a fixed instrument-microphone geometry. The reported acoustic response is used for

comparisons among rosette configurations under this geometry and does not represent a spatially integrated measurement of total radiated acoustic power.

Experimental Environment and Control Conditions

All measurements were conducted in the same room and measurement session under stable conditions. Joint rotation of the instrument and microphone was intended to reduce dependence on a single orientation of the assembly relative to the room while preserving the measurement geometry relative to the instrument. Residual room effects may nevertheless have influenced acoustic FRF magnitudes and closely spaced spectral features. The acoustic results are therefore interpreted primarily through comparisons among rosette configurations measured using the same geometry and acquisition procedure; these comparisons are not assumed to be free of room influence.

Temperature, relative humidity, and ambient-noise conditions were monitored throughout the session. The instrument, support system, excitation point, sensors, and acquisition settings remained unchanged except for the intended rosette substitution.

Data Processing and Comparative Analysis

For each condition, the complex bridge-mobility and force-normalized acoustic FRFs were compiled for direct comparison. When magnitudes were displayed logarithmically, levels were calculated as $20 \log_{10}$ of the FRF magnitude relative to $1 \text{ m s}^{-1} \text{ N}^{-1}$ for mobility and 1 Pa N^{-1} for the acoustic FRF. Geometric descriptors (total open area, regional open-area distribution, and total aperture-edge length) and mechanical comparison variables (progressive added mass and connectivity/stiffness-proxy configuration) were retained as separate explanatory variables. Interpretation focused on response differences observed under the standardized measurement procedure and on correspondence or divergence between structural mobility and radiated sound. Corresponding 50-2000 Hz spectra are

presented on logarithmic frequency axes in Supplementary Figures S9-S13; the original full-bandwidth measurement files were retained unchanged.

Peak frequencies were identified by visual inspection of the measured FRF spectra, guided by the expected low-frequency response regions and by locally prominent spectral maxima. This procedure was used to track comparable spectral features across conditions, rather than to establish an unambiguous modal identity for every peak. Where neighboring peaks were crowded, split, or insufficiently distinct for reliable correspondence, no unique modal correspondence was assumed. Accordingly, the reported peak comparisons should be interpreted as condition-dependent changes in selected spectral features, not as a fully automated or independently validated modal-tracking procedure.

The results are organized along three sequential experimental axes: geometric-acoustic variation, added mass, and connectivity/stiffness-proxy variation. For each axis, bridge mobility represents the local structural response at the bridge, whereas the force-normalized acoustic response represents the combined exterior radiation arising from soundboard motion and sound-hole radiation. Agreement between the two responses therefore strengthens a structural-acoustic interpretation, while divergence is not treated automatically as measurement error.

Geometric-Acoustic Effects of Rosette Design

Figure 5 summarizes the low-frequency acoustic FRFs for total openness, regional open-area distribution, and total aperture-edge length. In the openness series, the dominant Helmholtz resonance was no longer discernible as a comparable peak in the fully Closed condition; the weak local feature at 137.50 Hz was 25.21 dB below A1-G and 31.37 dB below the Open condition and should not be interpreted as preservation of the normal Helmholtz response. The

acoustic level in the approximately 220-225 Hz region was also reduced by about 8 dB under complete closure, and some higher-frequency resonances were attenuated, absent, or shifted. The Helmholtz-region peak remained effectively stable across the controlled foam-rosette subset, with an observed span of only 1.56 Hz, approximately equal to one FFT bin at the present spectral resolution. A remove-and-reinstall check was performed for the A4-G condition to assess the influence of remounting. The end-to-end level difference between A1 and A4 was 1.94 dB. Around 225 Hz, the acoustic response decreased from A1-G to A2-G, partially recovered at A3-G, and increased again at A4-G to approach the Open condition; this progression was non-monotonic (Figure 5b). The Open condition produced the clearest separation, shifting the selected Helmholtz-region peak to 145.31 Hz, while the general behavior of the other low-frequency regions remained closer to that of the rosette-installed conditions.

Complete sealing and complete opening therefore acted as informative acoustic boundary conditions, whereas the designed intermediate openness conditions produced comparatively smaller changes without a consistent monotonic trend across A1-A4. This non-monotonic response, together with the substantially larger changes observed at the boundary conditions, is consistent with coupled air-structure behavior in the real world and indicates that the observed response should not be reduced to the ideal Helmholtz relation alone. The loss of a comparable air-resonance peak under sealing agrees qualitatively with the disappearance of the Helmholtz peak when the guitar opening was sealed in Firth's (1977) controlled experiment; the accompanying structural-region changes here likewise show that closure perturbs a coupled system rather than only an isolated air oscillator. Full-range geometry spectra are provided in Supplementary Figures S9-S11.

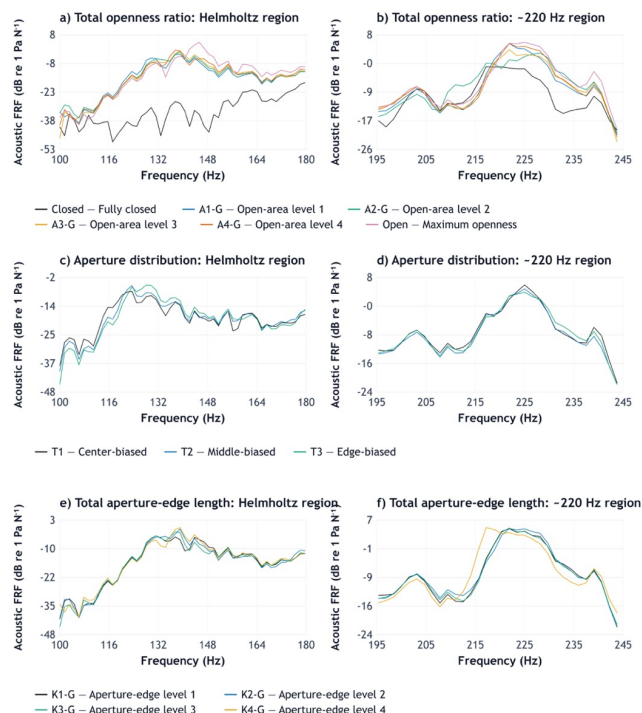


Figure 5. Low-frequency force-normalized acoustic responses for the geometry experiments: (a, b) total openness (Closed, A1-G-A4-G, and Open), (c, d) regional open-area distribution (T1-T3), and (e, f) total aperture-edge length (K1-G-K4-G). Left panels show the Helmholtz region; right panels show the low-frequency structural/modal region around 220 Hz.

Regional redistribution of open area produced distinct but limited changes across the measured response regions. Across T1-T3, the selected Helmholtz-region peak frequency spanned 4.69 Hz, while its level increased by 2.57 dB. In contrast, in the low-frequency structural/modal region around 220-225 Hz, the acoustic peak remained at 225.00 Hz for all three distributions, while its level decreased by 2.00 dB from the center-biased to the edge-biased condition. At lower frequency, the acoustic response contained a double-peaked or otherwise complex structure around 123 and 128-130 Hz; the level of the upper component increased by approximately 4.9 dB from T1 to T3. No unique modal identity is assigned to this structure. Bridge mobility showed a more nearly single peak around 223 Hz, whose level decreased by about 2.2 dB across T1-T3, while the lower-frequency mobility feature shifted from approximately 117 to 120 and 125 Hz. Thus, redistribution of the open area produced different response trends across frequency regions: the Helmholtz-region magnitude increased, whereas the acoustic response around 220-225 Hz decreased without a corresponding shift of its peak frequency. The contrast between the multi-peaked acoustic response and the more localized mobility response suggests that aperture distribution may affect radiated and mechanical responses differently.

In the aperture-edge-length series, the acoustic responses largely overlapped in the Helmholtz region, although the feature near 138-140 Hz was higher for K4-G than for K1-G. Neither the magnitude of this feature nor the selected peak frequency followed a strictly monotonic progression across all four conditions (Figure 5e). Around 220 Hz, the configurations differed more visibly in response shape (Figure 5f): K1-G-K3-G showed broadly similar elevated responses, whereas the maximum for K4-G occurred on the lower-frequency side of this region. The bridge-mobility response likewise showed a lower-frequency principal maximum for K4-G than for K1-G-K3-G (Supplementary

Figure S11b). The local magnitude increase between K1-G and K4-G near 138-140 Hz did not represent a uniform increase throughout the Helmholtz region, while the acoustic and bridge-mobility responses around 220 Hz showed configuration-dependent changes without a consistent monotonic progression across the complete series. Taken together, these observations show configuration-dependent differences without establishing a monotonic relation between total aperture-edge length and the measured peak responses. Acoustic FRF and bridge mobility describe different response quantities: the former is a force-normalized exterior sound-pressure response, whereas the latter is a local mechanical velocity response per unit force. Differences between their spectral shapes do not, by themselves, demonstrate mechanical-acoustic separation or identify a unique mechanism. Nia et al. (2015) relate near-edge airflow to aperture conductance and air-resonance radiation. These quantities are not equivalent to bridge mobility or to the acoustic FRF measured here, particularly in the structural/modal region around 220 Hz. Their findings therefore provide a possible physical context, but cannot establish an edge-length trend that is absent from the present response curves.

Taken together, the geometric comparisons showed different patterns across frequency regions and response quantities. Complete closure suppressed the prominent Helmholtz-region acoustic peak, while the Open condition placed the peak at a higher frequency than the installed-rosette conditions. Differences within the intermediate openness series were comparatively limited and did not follow a strictly monotonic progression. Regional redistribution of open area produced contrasting magnitude trends across frequency regions, with an increase in the Helmholtz-region response and a decrease around 220-225 Hz, while the latter peak remained at a similar frequency. In the aperture-edge-length series, K4-G showed a higher acoustic response than K1-G near 138-140 Hz, without a strictly monotonic

magnitude or peak-frequency progression across all four conditions; around 220 Hz, its principal maximum occurred at a lower frequency than those of K1-G-K3-G. Thus, the geometric comparisons did not reveal a single general monotonic relationship applicable to all measured regions and response quantities, although systematic trends were present for specific acoustic features. These observations support evaluating geometric effects separately for each frequency region and measured response and provide a reference for the added-mass and connectivity/stiffness-proxy series in the same instrument.

Effect of Rosette Mass

Figure 6 presents the complete physical sequence Open $\rightarrow$ M0 $\rightarrow$ M3 $\rightarrow$ M6 $\rightarrow$ M9.

Installing the normal K2-G rosette (Open $\rightarrow$ M0) shifted the acoustic Helmholtz-region peak from 145.31 to 129.69 Hz (-15.63 Hz) and reduced its level by 5.25 dB. In the low-frequency structural/modal region, the acoustic peak shifted from 223.44 to 218.75 Hz (-4.69 Hz), while its level changed by only -0.14 dB; the corresponding bridge-mobility peak level decreased by 6.65 dB. The installed rosette therefore affected both the Helmholtz region and the response around 220 Hz rather than acting only on the air resonance. This installation contrast must not be attributed to mass alone because the real rosette simultaneously introduces mass, stiffness, topology, and structural coupling. Full-range added-mass spectra are provided in Supplementary Figure S12.

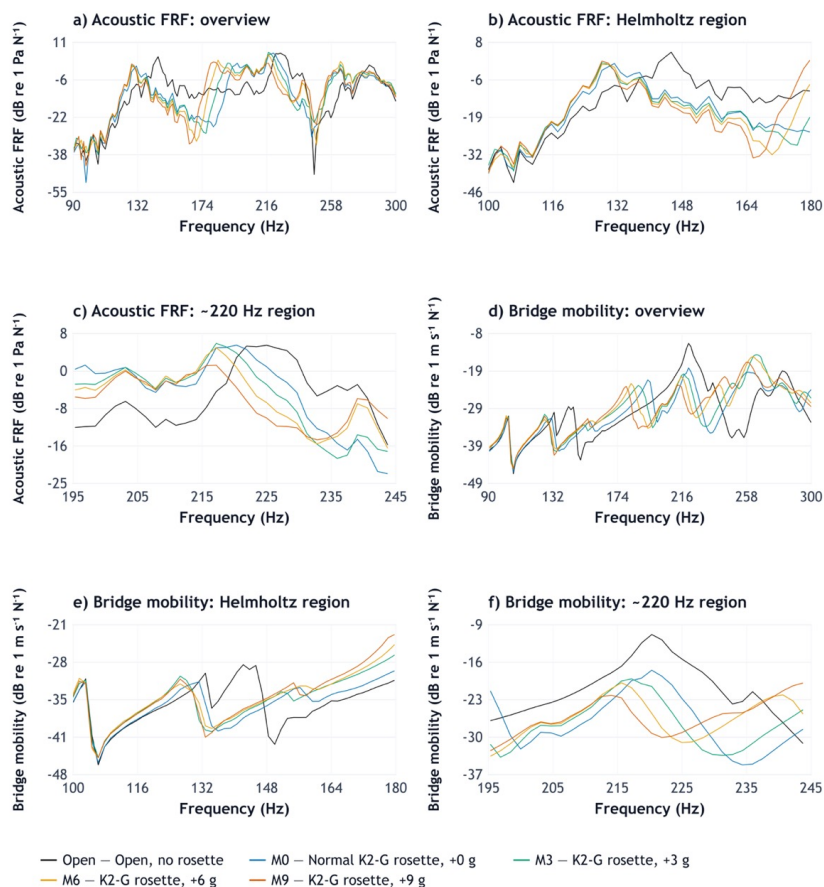


Figure 6. Force-normalized acoustic response (a-c) and bridge mobility (d-f) for the added-mass sequence Open, M0, M3, M6, and M9. Panels show the 90-300 Hz overview, Helmholtz region, and low-frequency structural/modal region around 220 Hz.

Within the controlled M0-M9 progression, the rosette geometry and configuration remained unchanged, and added mass was the intended experimental variable. The acoustic Helmholtz-region peak remained at 129.69 Hz for all four installed-rosette conditions, while its level changed non-monotonically within a 1.38 dB range. The selected acoustic structural-region peak moved from 218.75 Hz at M0 and M3 to 217.19 Hz at M6 and 215.63 Hz at M9. Relative to M0, its level changed by +0.09 dB at M3, -0.03 dB at M6, and -4.01 dB at M9. The acoustic peak-level changes were non-monotonic, with the largest reduction occurring at M9.

In the Helmholtz-frequency region of the bridge-mobility response, the Open condition showed a distinct response shape compared with the rosette-installed conditions, particularly around 135-150 Hz. The M0-M9 curves remained more closely grouped around the principal low-frequency mobility features, although smaller configuration-dependent differences persisted across the region. Bridge mobility showed the clearer mass-dependent evolution. The selected peak frequencies were 220.31, 217.19, 215.63, and 214.06 Hz for M0, M3, M6, and M9, respectively, while the peak levels relative to M0 were 0, -1.61, -2.33, and -4.67 dB. The selected bridge-mobility peak shifted downward in frequency and decreased in magnitude across M0-M9. This direction is consistent with beam experiments in which localized added mass reduced natural frequency most strongly where modal displacement was appreciable (Roohnia, 2026). Because the rosette mode shape was not measured, this comparison supports the direction of the effect but does not identify the rosette as a modal antinode. In the present instrument and within the tested mass range, added mass produced a comparatively regular structural-frequency progression and may therefore represent a candidate parameter for further controlled luthiery experiments. Although no linear model was fitted, the findings should not be

generalized beyond the measured sequence. The weaker and partly non-monotonic acoustic-amplitude evolution is physically plausible because bridge mobility describes a local structural transfer function, whereas the microphone response also combines soundboard and sound-hole radiation pathways. The limited change in the main Helmholtz-region peak across the controlled M0-M9 mass series, together with the clearer response changes around 220 Hz, indicates different sensitivities of the two regions rather than complete mechanical-acoustic decoupling.

Effect of Rosette Connectivity/Stiffness Proxy

Figure 7 compares the four connectivity/stiffness-proxy configurations F1-F4. The acoustic Helmholtz-region peak remained at 129.69 Hz in every condition, with a level span of 1.73 dB, indicating only limited sensitivity to the configuration change. In the low-frequency structural/modal region, the selected acoustic peak occurred at 220.31 Hz for F1 and F2, 218.75 Hz for F3, and 225.00 Hz for F4. Relative to F1, the corresponding peak levels changed by +1.38, -0.82, and -1.26 dB for F2, F3, and F4. Beyond these selected peak values, F4 also differed from F1-F3 in the overall response shape around 220 Hz, with a more prominent maximum on the higher-frequency side of the region and lower response levels over part of the lower-frequency side. The sequence was therefore non-monotonic and less regular than the added-mass progression, and should not be described as a linear or readily predictable one-factor geometry-based stiffness-proxy response. Because total aperture-edge length also co-varied across F1-F4, the measured differences cannot be attributed to physical stiffness alone. Full-range spectra are provided in Supplementary Figure S13.

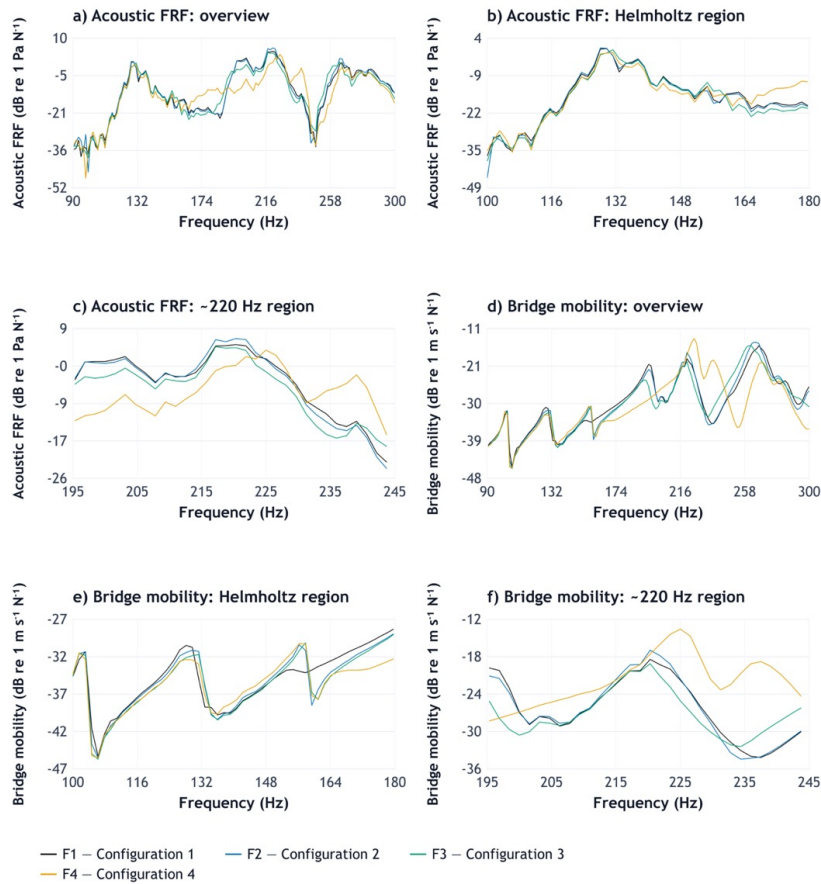


Figure 7. Force-normalized acoustic response (a-c) and bridge mobility (d-f) for connectivity/stiffness-proxy configurations F1-F4. Panels show the 90-300 Hz overview, Helmholtz region, and low-frequency structural/modal region around 220 Hz.

In the Helmholtz-frequency region, the bridge-mobility responses remained broadly similar across F1-F4, with local differences in response shape but no consistent ordering across the frequency range. In contrast, a more pronounced configuration-dependent separation emerged around 220 Hz. The mobility response provides stronger evidence of structural differentiation. In the unsmoothed bridge-mobility spectra shown in Figure 7f, the maximum within 195-245 Hz occurred at 220.31 Hz for F1-F3 and at 225.00 Hz for F4. Relative to the F1 maximum, the peak levels differed by +1.48 dB for F2, -0.69 dB for F3, and +4.85 dB for F4. F4 thus departs markedly from the preceding configurations in both peak position and mobility magnitude and

is the clearest departure from the earlier sequence.

The F4 departure is consistent with a change in coupled structural behavior and may reflect a stronger contribution from local rosette vibration or altered rosette-soundboard modal coupling. The documented aperture-edge-length co-variation is an additional plausible contributor. These remain physical interpretations rather than directly demonstrated mechanisms because rosette motion was not measured independently. The response may also depend on the attachment interface, contact and boundary conditions, and the adhesive used to couple the rosette to the soundboard. Localized stiffness and mass perturbations have different

sensitivities near nodes and antinodes in free-free wooden beams (Roohnia, 2026); this provides a relevant modal analogy, not a direct model of the rosette-soundboard assembly. More generally, the lack of one-to-one correspondence between mobility and force-normalized sound radiation is expected: a configuration can alter local bridge dynamics strongly while producing a smaller exterior acoustic change, or modify radiation pathways without an equally large mobility change. Accordingly, the connectivity/stiffness-proxy series did not show a response progression as regular as that observed for progressive added mass in the present configuration set.

Across the three experimental axes, the measured differences depended on frequency region and response quantity. The geometric comparisons showed visible changes, especially at the Closed and Open limits, but did not establish consistently monotonic responses to changes in the geometric descriptors. Within the installed-rosette mass series, the clearest ordered behavior was the downward frequency progression and decreasing magnitude of the selected bridge-mobility peak around 220 Hz; the acoustic peak magnitudes did not follow an equally regular progression. The F-series instead showed a marked departure at F4 and no monotonic progression across all configurations. Because physical stiffness was not independently quantified and aperture-edge length also varied, this series does not establish a predictable stiffness-dependent response. For the tested oud and configuration ranges, these findings support considering the rosette as a coupled geometric and mechanical component, while limiting claims of systematic adjustment to the particular response and sequence in which an ordered change was observed.

Conclusion

This study develops a controlled experimental framework for investigating the oud rosette as both a complex acoustic aperture and a mechanically coupled component. It

extends earlier descriptions based on open-area ratio, thickness, or material category by defining three geometric variables (total open area, regional open-area distribution, and total aperture-edge length) and two mechanical comparison series (progressive added mass and connectivity/stiffness-proxy configuration).

The use of interchangeable rosettes on one playable oud permits paired comparisons of bridge mobility and acoustic radiation at 1 m while the remainder of the instrument is held constant. The measurements indicate that rosette changes can modify the low-frequency response while several principal spectral features remain recognizable. Among the foam geometries, complete closure and opening produced the clearest boundary-condition effects, whereas regional distribution and aperture-edge length generated smaller, response-specific changes. Added mass produced the most regular evolution around 220 Hz, while the connectivity/stiffness-proxy series was less orderly and was dominated by the F4 departure. The framework therefore enables the geometric descriptors and added-mass progression to be evaluated in separate controlled sequences, while the F-series is interpreted as a connectivity/stiffness-proxy comparison with disclosed geometric co-variation.

For instrument making, the rosette is therefore best regarded neither as a purely decorative insert nor as an independently acting tonal control. Its potential contribution arises from its position within the coupled soundboard-cavity system. The measured mass progression suggests a possible route for controlled fine adjustment of the structural-region response, but the less regular connectivity/stiffness-proxy results and the divergence between mobility and radiation prevent a universal design prescription. Further work across multiple ouds, together with perceptual evaluation, will be required before these observations can be generalized to broader construction practice.

Recommendations

Future experiments should reproduce the geometric and mechanical comparisons on ouds with different soundboard, bowl, bracing, and sound-hole configurations. A multi-instrument design would establish whether the magnitude and direction of rosette-related changes are robust or depend on the baseline modal properties of a particular instrument.

Future mechanical series should distinguish added mass and independently measured physical stiffness as far as practicable and report the uncertainty and repeatability of their characterization. Attachment conditions, contact pressure, and adhesive behavior should also be documented because they may influence the effective boundary condition. Geometric series should likewise control total open area when testing regional distribution or aperture-edge length, thereby reducing covariance among the principal descriptors.

Finally, bridge mobility and radiated sound should be complemented by direct soundboard-velocity mapping, decay analysis, and player- or listener-based evaluations. These additions would help connect local structural changes, acoustic radiation, and perceived tonal differences without assuming that a measurable spectral change is necessarily perceptually salient.

Limitations of the Study

The study uses a single oud. This choice strengthens within-instrument control but limits generalization to instruments with different constructional and modal properties. The measured effects should therefore be interpreted as responses of the experimental instrument rather than universal characteristics of oud rosettes.

The geometric and mechanical descriptors may remain partially correlated in physically realizable rosettes. Changing an aperture pattern can alter mass and stiffness, while modifying thickness or material can affect

both mechanical properties. In F1-F4, total aperture-edge length also co-varied, so the series cannot isolate physical stiffness alone. Attachment, contact, and adhesive conditions may additionally influence effective coupling to the soundboard. Causal interpretation therefore depends on the extent to which each comparison set controls the remaining variables and on the reported uncertainty of those controls.

Frequency differences at or near one FFT bin were therefore treated as resolution-limited observations rather than definitive modal shifts.

Acknowledgements

The author gratefully acknowledges Ufuk Güler for providing the vector drawings of the traditional oud rosette patterns, and Aymen Rahmani for revising these drawings to enable their parametric and computational use.

Declaration of Use of AI

During the preparation of this work, OpenAI ChatGPT was used for language editing, translation assistance, refinement of data visualizations, and support in developing deterministic computational procedures for the parametric generation of rosette geometries.

The author reviewed and verified all AI-assisted outputs and retains full responsibility for the experimental data, analyses, interpretations, and conclusions. No experimental measurements were generated, fabricated, or modified by AI.

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Appendix 1. Supplementary Material

Controlled Geometric Analysis, Experimental Rosette Sets, and Full-Range Vibroacoustic Responses of the Oud

Traditional references, total openness, regional open-area distribution, aperture-edge length, added mass, connectivity/stiffness-proxy conditions, and full-range acoustic and bridge-mobility responses	
Geometric record count	50
Source-file manifest	41 non-system files; SHA-256 listed in Table S9
Active diameters	Large: 88.2 mm; Small: 40.5 mm
Theoretical material	3.0 mm PMMA; $\rho = 1.19 \text{ g cm}^{-3}$
Companion dataset	Supplementary_Data_Oud_Rosettes.xlsx and oud_rosette_master_data.csv https://doi.org/10.5281/zenodo.22681488
Scope of this supplement This document reports source-traceable geometric descriptors and experimental condition definitions. It does not calculate sound radiation, bridge mobility, Helmholtz resonance, or physical stiffness from rosette geometry. Those quantities must be obtained from the corresponding acoustic and vibration measurements.	

Contents and data products

Supplementary Methods: source control, radial zoning, geometric metrics, series definitions, mass calculation, and computational provenance.

Figures S1-S13: analytical framework, traditional geometries, controlled experimental series, mass placement, connectivity/stiffness-proxy series, and 50-2000 Hz acoustic and bridge-mobility spectra.

Tables S1-S7: variable definitions and group-specific quantitative descriptors.

Companion workbook Table S8: master data table containing all 50 rosette/condition records.

Companion workbook Table S9: complete source-file manifest with SHA-256 checksums.

Companion machine-readable files: XLSX workbook, master CSV, manifest CSV, QC/conflict JSON, and editable SVG figures.

Source audit and unresolved reporting constraints

The F1-F4 source files keep open area, regional distribution, and solid area constant, but internal aperture perimeter varies; the series is not a pure one-factor physical-stiffness series.

Relative proxy stiffness is a geometry-only normalized computational proxy, not a measured stiffness in N/m.

The measured baseline mass of the K2-G three-rosette set was 15.8 g, as reported in the main Methods. Added masses were documented separately; the total installed assembly mass was not independently reported.

Kapıdağlı İlyas large has 16 unmatched endpoints in the authoritative workbook QC and requires contour verification.

The Manol 1905 active diameters were derived as the outer disk diameter minus 6 mm, as explicitly documented in the workbook.

Regional perimeter values for traditional rosettes are new calculations from the supplied DXF contours. Values with >1% disagreement between the independent contour parser and workbook total are marked provisional.

PMMA mass calculations use 3.0 mm thickness and 1.19 g/cm³, the density encoded in the existing project analysis script; measured specimen masses were not supplied.

Supplementary Methods

S1. Source corpus, coding, and traceability

All non-system files in the supplied source directory and its subdirectories were inventoried before analysis. Existing design codes were retained verbatim. Each derived row in the master table carries its source path and a geometry/QC note. Companion workbook Table S9 lists file size and SHA-256 checksum, allowing later verification that the numerical tables and figures were generated from the same source corpus.

The experimental groups were classified as follows: traditional reference geometries; total open-area ratio (Closed, A1-G-A4-G, Open); regional open-area distribution (T1-T3); total aperture-edge length (K1-G-K4-G); added mass (Open, M0, M3, M6, M9) on the installed K2-G set; and the F1-F4 connectivity/stiffness-proxy series. The large and small active diameters were 88.2 and 40.5 mm, respectively.

S2. Equal-area radial partition

For an active sound-hole diameter D , the active radius was $R = D/2$. The disk was partitioned into center, middle, and edge zones of equal gross area using the analytical boundaries

$$r_1 = R/\sqrt{3}, \quad r_2 = R\sqrt{2/3}, \quad A_{\text{center}} = A_{\text{middle}} = A_{\text{edge}} = \pi R^2/3.$$

The regional open-area ratio was $\phi_i = A_{\text{open},i}/(\pi R^2/3)$, and the total open-area ratio was $\phi_T = \Sigma A_{\text{open},i}/(\pi R^2)$. The analytical boundaries were used only for measurement and were not laser-cut.

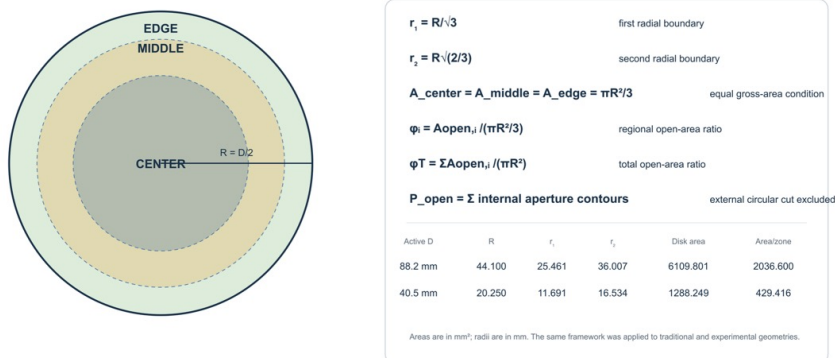


Figure S1. Equal-area radial framework used for all traditional and experimental geometries. The two analytical radii create three zones with identical gross area. Aperture area and aperture contour length were assigned to these zones.

S3. Aperture-area and aperture-edge-length definitions

Open area was defined as the area removed from the active disk. Total aperture-edge length, Popen, was the sum of internal aperture contours. The external circular cut used to detach the rosette from the sheet was excluded. Regional aperture-edge lengths were obtained by assigning or clipping internal contours to the equal-area zones; their sum was checked against Popen. Popen/D was retained as a dimensionless size-normalized geometric descriptor. It is not a substitute for an acoustic end-correction model.

The decision to preserve both open area and internal aperture perimeter as distinct descriptors is consistent with the emphasis on near-edge airflow in complex musical-instrument sound holes described by Tavakoli Nia (2010). In the present work, however, these descriptors remain strictly geometrical; no acoustic response was inferred from them.

S4. Traditional rosette normalization and contour analysis

Each traditional DXF was uniformly scaled to the appropriate active diameter. If D_s was the documented source diameter and D_t was the target active diameter, the scale factor was $s = D_t/D_s$; areas scale as s^2 and contour lengths as s . The authoritative total open area, total aperture-edge length, and original contour-QC fields were taken from the supplied traditional-analysis workbook. Regional areas and regional aperture-edge lengths were calculated from the supplied DXF contours using the equal-area partition.

For the two Manol 1905 files, the active diameter was not provided in the filename and was retained exactly as documented in the supplied workbook: outer-disk diameter minus 6 mm. The large Kapıdağlı İlyas geometry retained the workbook warning of 16 unmatched endpoints. Traditional regional aperture-edge values with more than 1% disagreement between the independent contour reconstruction and the authoritative workbook total are labelled provisional rather than silently corrected.

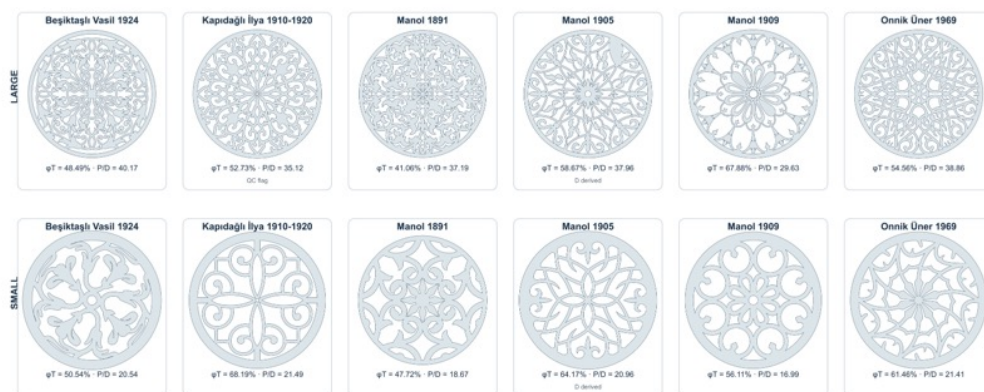


Figure S2. Complete traditional rosette reference set after size normalization. Large and small rows are drawn at a common display scale; quantitative values and QC status are provided in Table S2



Figure S3. Comparison of total openness, regional openness, and normalized aperture perimeter P/D for the traditional reference geometries. P/D is provided only as a dimensionless geometric descriptor

S5. Controlled experimental series

S5.1. Total open-area ratio

A1-G-A4-G form the controlled subset in which the center, middle, and edge open-area ratios are equal within each design and the total internal aperture perimeter is held constant within each diameter. Closed and Open are experimental boundary references. They do not belong to the fixed-perimeter subset; their internal aperture perimeter is zero under the stated definition because no internal aperture contour is present.



Figure S4. Total open-area series from Closed to Open. A1-G-A4-G are the fixed-internal-perimeter subset; only total open-area ratio changes systematically within that subset. Closed and Open are boundary references.

S5.2. Regional open-area distribution

T1, T2, and T3 contain 45 equal-diameter circular apertures and preserve total open-area ratio (18%) and total aperture-edge length within each diameter. The high-open-area zone is moved from center to middle to edge. The nominal regional ratios are 30/12/12%, 12/30/12%, and 12/12/30%, respectively.



Figure S5. Regional open-area distribution series. The total open area, total aperture-edge length, aperture count, and aperture diameter are controlled within a diameter; only the radial location of the high-open-area zone is changed.

S5.3. Total aperture-edge length

K1-G-K4-G preserve total and regional open-area ratios (49.1386%) within each diameter while aperture count and total aperture-edge length increase. Because the annular-sector widths and counts vary, the regional edge lengths are reported in addition to Popen. This group directly tests the effect of aperture-boundary extent at controlled openness.

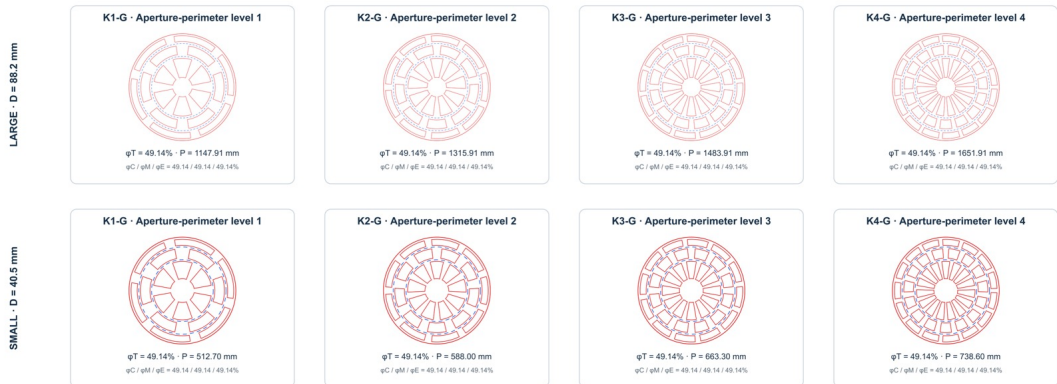


Figure S6. Aperture-edge-length series. Total and regional openness are controlled while aperture count and internal aperture perimeter increase from K1-G to K4-G.

S5.4. Added-mass conditions

The complete physical sequence was Open (no rosette) → M0 → M3 → M6 → M9. For M0-M9, the installed reference geometry was one large and two small K2-G rosettes. Added masses of 0, +3, +6, and +9 g were applied sequentially at the documented placement, with M0 denoting no additional mass. The component geometry was unchanged across the four installed-rosette conditions. The theoretical PMMA mass of the three-rosette set is 15.772 g, whereas its measured baseline mass was 15.8 g, as reported in the main Methods. Added masses are reported separately; the total installed assembly mass was not independently reported.



Figure S7. Added-mass experiment based on the fixed K2-G component set for M0, M3, M6, and M9. The source photograph documents mass placement. The measured baseline rosette-set mass was 15.8 g; nominal added masses were 0, +3, +6, and +9 g. The added masses are experimental increments and are not estimates of the total installed assembly mass.

S5.5. Connectivity/stiffness-proxy conditions

F1-F4 preserve active total openness (47.56%), regional openness (47.56% in each equal-area zone), and solid area within a diameter. Connectivity is changed through the number and curvature of continuous trunks and the number of complete rings. The supplied relative stiffness values are geometry-only proxy values, normalized to F1 = 1 independently within each diameter. The proxy was defined in the source as the reciprocal of compliance obtained from two successive grounded graph-Laplacian solves under a unit load on the common center ring.

These values are not physical stiffness in N/m and were not validated by a mechanical calibration. Furthermore, internal aperture perimeter varies across F1-F4 (large: 1240.259-1736.450 mm; small: 569.507-797.350 mm). The series must therefore be reported as a connectivity/stiffness-proxy experiment with a documented aperture-perimeter co-variation, not as an unconfounded one-factor stiffness experiment.

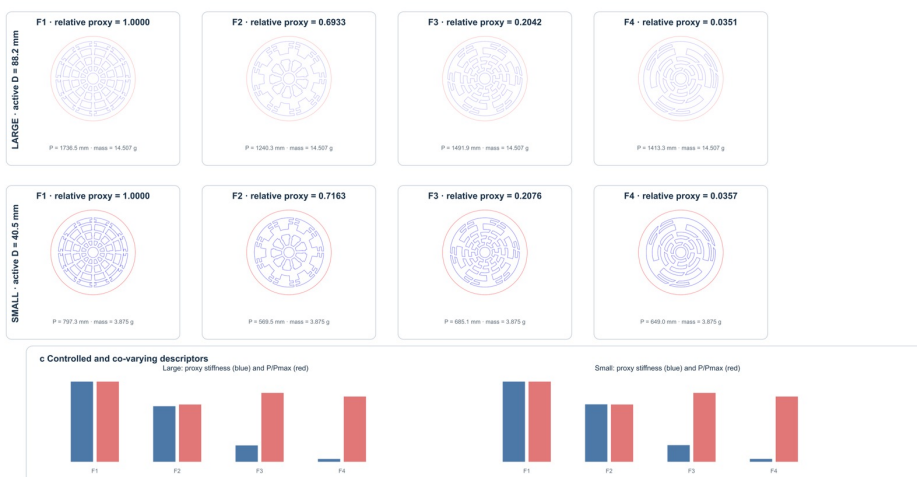


Figure S8. Connectivity/stiffness-proxy series. The geometries preserve open area, its radial distribution, and calculated PMMA mass within each diameter, while connection topology and the geometry-only relative proxy change. Internal aperture perimeter is disclosed because it is not controlled.

S6. Theoretical PMMA mass

For a geometry represented by solid planar area A_{solid} , the theoretical mass was calculated as

$$m_{\text{PMMA}} = A_{\text{solid}} \cdot t \cdot \rho / 1000,$$

where A_{solid} is in mm^2 , thickness $t = 3.0 \text{ mm}$, density $\rho = 1.19 \text{ g cm}^{-3}$, and the result is in grams. For flanged F-series geometries, A_{solid} includes the documented outer flange. For traditional designs, it refers to the complete scaled outer disk minus all apertures. The results are theoretical manufacturing values and should not be reported as measured specimen mass.

S7. Computational provenance and AI-assisted workflow

An AI-assisted coding environment was used to inventory the files, execute deterministic geometry calculations, generate the master data table, and assemble the figures and document. Existing codes and source values were preserved. No acoustic result, physical stiffness, base-rosette mass, or missing geometric value was synthesized. Source conflicts and absent values were retained as explicit QC statements. The machine-readable workbook contains the group-specific tables, complete master table, source paths, and QC log used to generate this document.

Table S1. Definitions and reporting conventions

Symbol	Definition	Unit	Reporting rule
D	Active sound-hole diameter	mm	88.2 (large) or 40.5 (small)
R	Active radius	mm	D/2
r_1	Center-zone boundary radius	mm	$R/\sqrt{3}$
r_2	Middle/edge boundary radius	mm	$R/\sqrt{2/3}$
$A_{\text{open},i}$	Open area assigned to radial zone i	mm^2	Center, middle, or edge
φ_i	Regional open-area ratio	%	$A_{\text{open},i} / (\pi R^2/3)$
φ_T	Total open-area ratio	%	$\sum A_{\text{open},i} / (\pi R^2)$
Popen	Total internal aperture-edge length	mm	External circular cut excluded
Popen/D	Normalized aperture-edge length	—	Dimensionless geometric descriptor
mPMMA	Theoretical mass of 3 mm PMMA geometry	g	$\rho = 1.19 \text{ g cm}^{-3}$; not measured mass

Quantitative table

Table S2. Traditional rosette geometry after normalization to the experimental active diameters.

Code	Traditional attribution	Size	D	Source D	Scale	φT (%)	$\varphi C/\varphi M/\varphi E$ (%)	Popen (mm)	PC/PM/PE (mm)	P/D	mPMMA (g)	QC
vasil_buyuk_1924	Besiktaşlı Vasil 1924	Large	88.2	92.000	0.95870	48.49	45.73/48.74/51.01	3,543.107	1,189.96/1,254.61/1,098.54	40.171	14.172	Accepted
ilya_buyuk_1910_1920	Kapıdağlı İlyâ 1910-1920	Large	88.2	83.000	1.06265	52.73	46.46/51.45/60.28	3,097.807	1,016.22/929.91/1,151.68	35.123	13.579	Provisional regional P
manol_buyuk_1891	Manol 1891	Large	88.2	104.000	0.84808	41.06	38.13/46.15/38.90	3,280.392	1,100.61/938.91/1,240.88	37.193	15.618	Provisional regional P
manol_buyuk_1905	Manol 1905	Large	88.2	87.953	1.00281	58.67	59.25/60.07/56.68	3,348.287	1,196.98/942.96/1,208.34	37.962	12.092	Provisional regional P
manol_buyuk_1909	Manol 1909	Large	88.2	83.000	1.06265	67.88	59.05/83.97/60.62	2,613.219	1,092.10/488.31/1,032.81	29.628	10.274	Provisional regional P
onnik_buyuk_1969	Onnik Üner 1969	Large	88.2	83.000	1.06265	54.56	49.06/54.29/60.33	3,427.858	1,095.31/1,112.59/1,219.96	38.865	13.178	Accepted
vasil_kucuk_1924	Besiktaşlı Vasil 1924	Small	40.5	38.000	1.06579	50.54	57.99/37.89/55.73	831.888	187.51/265.26/379.11	20.540	3.842	Accepted
ilya_kucuk_1910_1920	Kapıdağlı İlyâ 1910-1920	Small	40.5	43.000	0.94186	68.19	72.57/65.60/66.38	870.537	241.20/247.31/382.03	21.495	2.836	Accepted
manol_kucuk_1891	Manol 1891	Small	40.5	40.000	1.01250	47.72	26.41/61.14/55.61	756.114	298.12/199.04/258.95	18.669	3.122	Accepted
manol_kucuk_1905	Manol 1905	Small	40.5	40.000	1.01250	64.17	67.08/66.09/59.35	848.887	297.26/269.36/282.27	20.960	3.131	Accepted
manol_kucuk_1909	Manol 1909	Small	40.5	43.000	0.94186	56.11	42.72/73.36/52.24	688.109	277.25/134.13/276.73	16.990	3.392	Accepted
onnik_kucuk_1969	Onnik Üner 1969	Small	40.5	43.000	0.94186	61.46	50.24/65.22/68.93	866.945	285.78/263.06/318.11	21.406	3.145	Accepted

Note: The source-file design code is retained. Regional perimeter is derived by clipping the supplied DXF aperture contours to equal-area zones and reconciling the regional sum to the authoritative workbook total. Manol 1905 source D is derived as documented in that workbook.

Table S3. Total open-area ratio series, including Closed and Open boundary references

Size	Code	Condition	D	φT (%)	Aopen (mm ²)	$\varphi C/\varphi M/\varphi E$ (%)	Popen (mm)	PC/PM/PE (mm)	P/D	mPMMA (g)	Control/QC
Large	Closed	Closed reference	88.2	0.000	0.000	0.000/0.000/0.000	0.000	0.00/0.00/0.00	0.000	—	Reference condition; not part of the fixed-perimeter A1-G-A4-G subset
Large	A1-G	Open-area level 1	88.2	37.367	2,283.068	37.367/37.367/37.367	1,401.411	539.52/412.90/448.99	15.889	13.661	Source SVG; controlled geometry
Large	A2-G	Open-area level 2	88.2	44.146	2,697.222	44.146/44.146/44.146	1,401.411	493.61/421.56/486.24	15.889	12.183	Source SVG; controlled geometry
Large	A3-G	Open-area level 3	88.2	50.924	3,111.377	50.924/50.924/50.924	1,401.411	447.70/430.21/523.49	15.889	10.704	Source SVG; controlled geometry
Large	A4-G	Open-area level 4	88.2	57.703	3,525.531	57.703/57.703/57.703	1,401.411	401.80/438.87/560.75	15.889	9.226	Source SVG; controlled geometry
Large	Open	Open reference	88.2	100.000	6,109.801	100.000/100.000/100.000	0.000	0.00/0.00/0.00	0.000	0.000	Reference condition; not part of the fixed-perimeter A1-G-A4-G subset
Small	Closed	Closed reference	40.5	0.000	0.000	0.000/0.000/0.000	0.000	0.00/0.00/0.00	0.000	—	Reference condition; not part of the fixed-perimeter A1-G-A4-G subset
Small	A1-G	Open-area level 1	40.5	37.367	481.384	37.367/37.367/37.367	626.759	233.25/190.10/203.42	15.476	2.881	Source SVG; controlled geometry
Small	A2-G	Open-area level 2	40.5	44.180	569.144	44.180/44.180/44.180	626.759	215.76/191.59/219.42	15.476	2.567	Source SVG; controlled geometry
Small	A3-G	Open-area level 3	40.5	50.992	656.904	50.992/50.992/50.992	626.759	198.27/193.08/235.41	15.476	2.254	Source SVG; controlled geometry
Small	A4-G	Open-area level 4	40.5	57.804	744.663	57.804/57.804/57.804	626.759	180.78/194.57/251.41	15.476	1.941	Source SVG; controlled geometry
Small	Open	Open reference	40.5	100.000	1,288.249	100.000/100.000/100.000	0.000	0.00/0.00/0.00	0.000	0.000	Reference condition; not part of the fixed-perimeter A1-G-A4-G subset

Note: A1-G-A4-G constitute the fixed-Popen controlled subset. Closed and Open are boundary references and therefore do not share the internal-perimeter constraint. PMMA mass is not assigned to those references because the source does not define physical reference inserts.

Table S4. Regional open-area distribution series.

Size	Code	Bias	D	φT (%)	Aopen (mm ²)	$\varphi C/\varphi M/\varphi E$ (%)	Popen (mm)	PC/PM/PE (mm)	Apertures	mPMMA (g)
Large	T1	Center-biased	88.2	18.00	1,099.764	30.0/12.0/12.0	788.610	438.12/175.25/175.25	45	17.886
Large	T2	Middle-biased	88.2	18.00	1,099.764	12.0/30.0/12.0	788.610	175.25/438.12/175.25	45	17.886
Large	T3	Edge-biased	88.2	18.00	1,099.764	12.0/12.0/30.0	788.610	175.25/175.25/438.12	45	17.886
Small	T1	Center-biased	40.5	18.00	231.885	30.0/12.0/12.0	362.120	201.18/80.47/80.47	45	3.771
Small	T2	Middle-biased	40.5	18.00	231.885	12.0/30.0/12.0	362.120	80.47/201.18/80.47	45	3.771
Small	T3	Edge-biased	40.5	18.00	231.885	12.0/12.0/30.0	362.120	80.47/80.47/201.18	45	3.771

Note: There are 45 equal-diameter circular apertures in every T design. The nominal source ratios, rather than sub-rounding differences from SVG coordinates, are reported.

Table S5. Aperture-edge-length series at controlled total and regional openness.

Size	Code	D	φT (%)	Aopen (mm ²)	$\varphi C/\varphi M/\varphi E$ (%)	Popen (mm)	PC/PM/PE (mm)	P/D	Apertures	Per zone	mPMMA (g)
Large	K1-G	88.2	49.1386	3,002.271	49.1386/49.1386/49.1386	1,147.905	316.42/361.87/469.61	13.015	18	6	11.094
Large	K2-G	88.2	49.1386	3,002.271	49.1386/49.1386/49.1386	1,315.905	411.44/405.65/498.81	14.920	27	9	11.094
Large	K3-G	88.2	49.1386	3,002.271	49.1386/49.1386/49.1386	1,483.905	506.46/449.43/528.02	16.824	36	12	11.094
Large	K4-G	88.2	49.1386	3,002.271	49.1386/49.1386/49.1386	1,651.905	601.47/493.21/557.22	18.729	45	15	11.094
Small	K1-G	40.5	49.1386	633.028	49.1386/49.1386/49.1386	512.702	143.12/159.57/210.01	12.659	18	6	2.339
Small	K2-G	40.5	49.1386	633.028	49.1386/49.1386/49.1386	588.002	182.67/181.42/223.91	14.519	27	9	2.339
Small	K3-G	40.5	49.1386	633.028	49.1386/49.1386/49.1386	663.302	222.22/203.28/237.81	16.378	36	12	2.339
Small	K4-G	40.5	49.1386	633.028	49.1386/49.1386/49.1386	738.602	261.77/225.13/251.70	18.237	45	15	2.339

Note: The external circular cut is excluded. All P values are computed analytically from the annular-sector source paths.

Table S6. Added-mass conditions M0, M3, M6, and M9 for the installed K2-G rosette set.

Condition code	Installed condition	Installed geometry	Added mass (g)	Aopen,set (mm ²)	$\varphi C/\varphi M/\varphi E$ (%)	Popen,set (mm)	PC/PM/PE (mm)	Theoretical PMMA set mass (g)	Measured base mass (g)	Total assembly mass
M0	K2-G with 0 g additional mass	1 large (88.2 mm) + 2 small (40.5 mm) K2-G rosettes	0.0	4,268.326	49.1386/49.1386/49.1386	2,491.910	776.78/768.49/946.63	15.772	15.8	Not reported
M3	K2-G with +3 g additional mass	1 large (88.2 mm) + 2 small (40.5 mm) K2-G rosettes	3.0	4,268.326	49.1386/49.1386/49.1386	2,491.910	776.78/768.49/946.63	15.772	15.8	Not reported
M6	K2-G with +6 g additional mass	1 large (88.2 mm) + 2 small (40.5 mm) K2-G rosettes	6.0	4,268.326	49.1386/49.1386/49.1386	2,491.910	776.78/768.49/946.63	15.772	15.8	Not reported
M9	K2-G with +9 g additional mass	1 large (88.2 mm) + 2 small (40.5 mm) K2-G rosettes	9.0	4,268.326	49.1386/49.1386/49.1386	2,491.910	776.78/768.49/946.63	15.772	15.8	Not reported

Note: The theoretical set mass is 1 large + 2 small K2-G component masses. It is not a measured installed mass. Added mass remains a separate experimental variable.

Table S7. Connectivity/stiffness-proxy series and disclosed geometric co-variation.

Size	Code	Configuration	Active D	Outer D	Trunks	Rings	Sweep (°)	φT (%)	$\varphi C/\varphi M/\varphi E$ (%)	Popen (mm)	P/D	mPMMA (g)	Relative proxy	Proxy compliance
Large	F1	Twelve straight trunks + three rings	88.2	94.2	12	3	0.0	47.5600	47.5600/47.5600/47.5600	1,736.450	19.688	14.507	1.0000	205.183
Large	F2	Nine trunks + one ring	88.2	94.2	9	1	3.0	47.5600	47.5600/47.5600/47.5600	1,240.259	14.062	14.507	0.6933	295.970
Large	F3	Six curved trunks, no full ring	88.2	94.2	6	0	28.0	47.5600	47.5600/47.5600/47.5600	1,491.904	16.915	14.507	0.2042	1,004.879
Large	F4	Three spiral trunks, no full ring	88.2	94.2	3	0	80.0	47.5600	47.5600/47.5600/47.5600	1,413.348	16.024	14.507	0.0351	5,849.506
Small	F1	Twelve straight trunks + three rings	40.5	46.5	12	3	0.0	47.5600	47.5600/47.5600/47.5600	797.350	19.688	3.875	1.0000	212.062
Small	F2	Nine trunks + one ring	40.5	46.5	9	1	3.0	47.5600	47.5600/47.5600/47.5600	569.507	14.062	3.875	0.7163	296.057
Small	F3	Six curved trunks, no full ring	40.5	46.5	6	0	28.0	47.5600	47.5600/47.5600/47.5600	685.058	16.915	3.875	0.2076	1,021.659
Small	F4	Three spiral trunks, no full ring	40.5	46.5	3	0	80.0	47.5600	47.5600/47.5600/47.5600	648.986	16.024	3.875	0.0357	5,944.504

Note: Relative proxy is normalized to F1 within each diameter and is not physical stiffness in N/m. Open area, radial distribution, and solid area are controlled, but Popen varies.

S8. Full-Range Frequency-Response Plots (50-2000 Hz)

All panels use a logarithmic frequency axis from 50 to 2000 Hz. Acoustic panels show the force-normalized acoustic FRF $H_p = p/F$ in dB re 1 Pa N^{-1} , and mechanical panels show bridge mobility $Y = v/F$ in dB re 1 $m s^{-1} N^{-1}$.



Figure S9. Full-range force-normalized acoustic FRF and bridge-mobility spectra for the total open-area ratio series, ordered from Closed through A1-G-A4-G to Open (50-2000 Hz; logarithmic frequency axis)

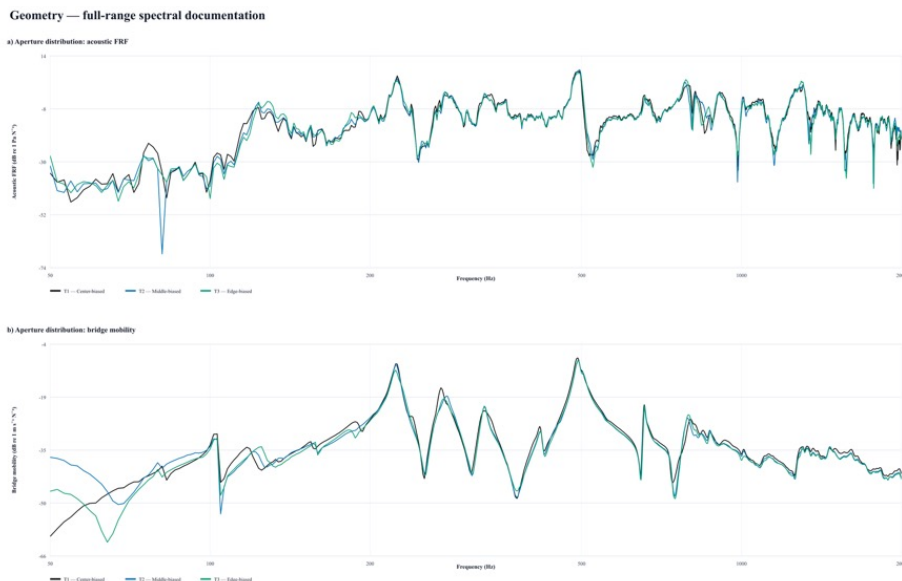


Figure S10. Full-range force-normalized acoustic FRF and bridge-mobility spectra for the regional open-area distribution series T1-T3 (50-2000 Hz; logarithmic frequency axis)

Geometry — full-range spectral documentation



Figure S11. Full-range force-normalized acoustic FRF and bridge-mobility spectra for the total aperture-edge-length series K1-G-K4-G (50-2000 Hz; logarithmic frequency axis)

Added Mass — full-range spectral documentation



Figure S12. Full-range force-normalized acoustic FRF and bridge-mobility spectra for the physical added-mass sequence Open, M0, M3, M6, and M9 (50-2000 Hz; logarithmic frequency axis)



Figure S13. Full-range force-normalized acoustic FRF and bridge-mobility spectra for the connectivity/stiffness-proxy configurations F1-F4 (50-2000 Hz; logarithmic frequency axis)

Supplementary Reference

Tavakoli Nia, H. (2010). *Acoustic function of sound hole design in musical instruments*. Master's thesis. Massachusetts Institute of Technology. US

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