SONIC DOMES

Solving acoustic performance of curved surfaces by interfacing parametric design, structural engineering and acoustic analysis

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Abstract. This paper addresses the acoustic performance of complex curved surface geometries that are commonly known to pose problems of sound concentration, thus affecting speech intelligibility and audience experience in spaces of temporal arts performance. It reviews an open system of design research in which parametric design process, structural analysis and acoustic analysis are deployed to improve the sound of ellipsoidal structures in relation to sound source and audience positions, by adapting the height, dimension and centre point of a dome structure, consequently improving the acoustic behaviour of the performance space. The paper discusses an iterative design, analysis and optimization processes, in which a number of generative form variations were developed in Grasshopper, and reworked in McNeel Rhino, tested in engineering software (Strand7), and evaluated in acoustic simulation (ODEON). This allowed an interdisciplinary team to develop, test and evolve a design proposal that shows one solution for avoiding sound concentration and consequently improving acoustic performance in complex intersecting and curved geometries of a multifunctional building.

Keywords. Parametric design; sound concentration; curved surfaces; structural engineering; acoustic simulation.

1. Introduction of Context: Acoustic Performance of Curved Surfaces

This research investigates the acoustic performance of curved surface geometries by employing variations of parametric models to evaluate spatial, structural and perceptual criteria. Specifically, the quality of spaces for spoken word is dependent on a good understanding of the relationships between geometry and acoustic performance, and their impact on speech intelligibility and soundscape unfolding for the
spectator. Several different options of curved surfaces in relation to circular and circle-intersecting volumes are tested through computational acoustic analysis techniques suitable for the prediction of sound concentration. The research discusses the acoustic properties of complex geometries with curved surfaces, and reviews how the acoustic performance can be modified through geometry manipulations.

Generative design offers a tight control of duration, force flow, structural deformation, material agencies, and spatial behaviour. In complex curved structures, a catenary logic (self-regulation and optimisation of structures in response to internal force flows) may be applied to solve structural requirements. An acoustic optimisation is usually performed at the end of a design process by the introduction of absorbing materials or amplification, instead of geometrical optimisation using acoustic simulation as an integral part of the design process. Yet, specifically in spaces for temporal arts, the acoustic performance of generative and structural variations is critical. (Reinhardt et al., 2012). When parametric design, structural analysis and resulting acoustic simulation are interfaced in analytical cycles, complex curved morphologies can be designed without retreating to secondary sound improvement measures, through reviewing the performative criteria in direct relation to the geometry.

The context of the research is a design with four interlocking domes, which answered structural requirements set by extreme lateral and vertical forces, but posed a challenging acoustic behaviour due to sound concentration resulting from an ellipsoid geometry. Thus, the research employs the creation of a parametric model and structural and acoustic simulation transfers, to enable an improved acoustic performance of curved surface geometries. The paper presents an open agenda between different collaborative realms; the generative digital design as realm of strategic design (3D modelling in McNeel Rhinoceros and scripting in McNeel plugs-ins: Grasshopper); the structural analysis realm as area of construction requirements (Finite Element Analysis in Strand7); and the acoustic analysis as an arena of the immersive experience (simulation in B&K ODEON), in order to provide a platform in which different partners of a collaborative team can interact.

2. Performative Spaces: Reflections, Reverberation, Speech Intelligibility and Simulation

In acoustics, a number of descriptors serve to identify the relationship between materials, architectural configuration and perceived sound characteristics, which aid design for temporal arts spaces (theatre plays, concerts, or dance performances). Sound Reflection seldom exists in isolation; sound will almost always find a surface on its path, where a reflection will be created. Understanding how a material reflects sound is an important step in making predictions of the behaviour of sound in a room, as all surfaces reflect and absorb to an extent. Reverberation Time is one of the most common acoustic descriptors of a space. Depending on the
absorption coefficient of surfaces, sound will be absorbed and reflected creating a reflection pattern that governs perceptual acoustic characteristics of rooms. *Speech intelligibility* refers to the ability of a listener to understand speech on a given acoustical situation, and is intrinsically related to reflection patterns of sound. Speech intelligibility can be increased by early reflections that increase the level of a speaker in a room. Yet when reflections arrive at a later time, the beneficial effects of reflections reverse as earlier utterances mask later utterances, therefore degrading speech intelligibility. Speech intelligibility may also suffer with unfavourable acoustic conditions such as strong late reflection (echoes) and sound focusing due to specific geometries of a space (Reinhardt et al., 2012). *Acoustic Simulation* enables the critical investigation of an acoustic performance in the design and revision of existing and future spaces. Through acoustic simulation, relationships between source, reflection patterns and acoustic descriptors at a receiving point can be used to determine the quality of acoustic performances.

### 3. Acoustical Phenomena and Concentration in Complex Curvatures

When sound encounters a surface it can be absorbed, reflected, diffracted or transmitted, and will, depending on the spatial morphology, result in different acoustic responses in terms of sound reflection. Acoustical phenomena associated with curved surfaces can introduce entertaining auditory characteristics in a space, for example the presence of an echo (distinct and late repetition of a sound) or the so-called whispering galleries (multiple reflections travelling distances along a curved surface). An early example can be found in ‘Phonurgia Nova’ (Kircher, 1666), a curved geometry is described that causes a sound amplification and increased speech intelligibility between two points, in an unexpected way.

With the introduction of wave theory of optics (Huygens, 1690), the acoustic behaviour can be modelled following principles of optical geometrics, in which rays are used to demonstrate wave propagation; that is, sound is treated similar to light by which the exit angle of a ray reflecting from a surface equals its complementary entrance angle with respect to the normal of the surface. Different concentration patterns result as the geometry changes from a circle to an ellipse. In spaces with a circular ground plane (with a centre based sound source), sound rays meet the wall at same time, are reflected, and a sound wave will converge simultaneously upon the original source position. Sound waves that form a successive wavefront through secondary sound reflections will result in sound concentration at a particular point (Cremer and Mueller, 1982). Furthermore, rays in an ellipsoid will concentrate in two opposite focal points.

In complex designs with a spherical morphology, sound concentration caused by curved surfaces can cause uneven sound distribution in the audience area, and lead to negative effects such as low speech intelligibility, specifically as reflection
characteristics are exacerbated by the use of hard materials. Surfaces curved in two directions such as spheres or ellipsoids would usually result in strong sound focusing which negatively affect the acoustic experience. This poses an evident problem in spaces that require good listening conditions, as is the case in temporal art (Cremer and Mueller, 1982; Vercammen, 2012). We understood this as a challenge to revise directly complex curved geometries through iterative revision and innovative use of parametric and analytical design methodologies, undertaking a research that demonstrates that acoustic performances in ellipsoidal spheres can be acceptable if the geometry is integrated with acoustic simulation.

4. Sonic Domes: Case Study

The problem of acoustic behaviour of complex curved surfaces in an architecture based on complex intersecting ellipsoid spheres is revised in the proposal for a cultural centre in Nagano prefecture, Japan (Figure 1), designed to withstand the seismic and environmental effects of the region, lateral force waves of earthquake scenarios and vertical stress by extreme exposure to temporary snow loads (3.3m equal 1t/m²). This context deviates from classical temporal arts spaces through a multifunctional design brief, whereby acoustic behaviour is an integral but nonexclusive parameter. ‘Sonic Domes’ is modelled as a series of intersecting spheres, to answer requirements of structure and performance, in contrast to single ellipsoidal sphere sections that commonly define stage and auditorium spaces in temporal arts.

Structurally, the design proposes a dome as an ideal formation for earthquake secure buildings. This responds to structural requirements of extreme stresses as caused by temporary imposition of loads, based on a circular geometry with a centre of gravity oriented in the lower section. Spatially, the interlocked ellipsoidal spheroids allow a dynamic flow of varying spatial volumes that can be adapted to temporary programmatic requirements, with fluent transitions between internal intersections and adjacency of zones. The processes of developing the project between the different team members proceeded as iterative design and analysis through different
steps at which end data were exchanged; from (1) construction of intersecting spheres in 3D modelling software (McNeel Rhino); to (2) an initial acoustic analysis to identify position of sound source in major volumes (ODEON); back to (3) parameterization of structural system to deflect geometry (McNeel Plugin Grasshopper); to (4) finite element analysis of structure (Strand7); and (5) evaluating final acoustic simulation (ODEON). In this ‘reverse engineered’ process, the acoustic forecast becomes the descriptor for formal, perceptual and structural solution.

5. Loop 1: 3D Modelling and Initial Analysis of Curved Surface Geometry

‘Sonic Domes’ is constructed as ellipsoidal spheres in 3D modelling software, whereby spheres with varying dimensions (resulting in major and minor volumes) are inscribed as intersecting rings of steel in base plan, with a calculated potential to absorb lateral seismic forces. The primary supporting steel columns arise as three-dimensional cross bracing from the base intersections, and define embedded triangulated spatial cores. A secondary structural system of plywood timber beams complements beams and articulates each sphere, and its intersection on the base plane, and three-dimensionally along the curvature of the spheres. A tessellated system of planar elements (timber shingles) forms the exterior skin, following the surface curvature (Figure 2, a). In the main volumes, the ideal geometry of intersecting ellipsoidal spheres is manipulated along the centre section line, so that the resulting geometry opens at the upper part to let natural light in (Figure 2, b).

The spheres follow the logic of force-response of ideal catenaries structures \(b = h + a\), \(ie \frac{1}{2}b > a\) for optimum). The performance of curvature was initially assessed by the architect through a number of criteria; the overall intersection of spheres; the distribution of seams and openings; the homogeneity within radii; the Gaussian Bell Curve distribution; and default points within the surface curvature.

![Figure 2](https://example.com/figure2.png)

Figure 2. 3D model with base plate, spheres and structural beams (a), system of interlocking spheres and manipulation of curved geometry (b).
under high light reflection; and possible solutions for planar tesselation (Figure 3, a). The resulting data were exchanged with a structural engineer. A Finite Element analysis in Strand7 compared stress behaviour in the spheres modelled as rigid shell structure, and as beam system (Figure 3, b). A beam system would be more readily constructed, expected to be more cost effective and would incorporate steel and timber framing elements for reduced mass and improved ductility and performance in an earthquake event in comparison to a concrete shell structure. The result identifies that while an efficient structural performance can be achieved in both cases, the beam system requires also the insertion of a rigid frame for the openings in order to address critical moments in the sphere.

With the structural requirements solved, the programmatic brief included a requirement of unamplified vocal performances, with even distribution of sound levels across the entire audience area. Providing a similar experience to all audience members with high speech intelligibility at all locations within the audience area was an important acoustic parameter in the design process. Given that the problem of sound concentration in curved surfaces was well known, the design had to be tested for its acoustic performance. The next step was an initial analysis, whereby the original 3D data (Rhino) were exported as 3dsfiles (3DStudioMax) to acoustic modelling software (ODEON), where they were parameterized and sufficiently segmented to allow a close acoustic analysis. In a spherical geometry, rays are concentrated in a focus point, with a uniform distribution, where propagation distances of sound paths are described as equal depend on the particular point the performer takes. We tested two source positions in a deflected geometry (spherical deflected dome with opening), in order to understand how sound rays reflected when positioned in the major volumes, and to test the resulting speech intelligibility (Figure 4).

While the expectation was that the sound would concentrate negatively through reflections and sound concentration, the acoustic simulation showed the intersected domes not only proved an ideal formation in structural analysis, but
also their acoustic behaviour was acceptable – taking into account that the original geometry of the sphere was deflected, and the sources were ideally positioned.

6. Loop 2: Final Specification of Curved Surface Geometry through Acoustic Behaviour

In order to test the outcome of different architectural configurations, several parameter changes of the original sphere geometry were scripted as height and diameter variations, and as shift of central sphere point in the original ideal sphere shapes: several more variations were developed in a scripting environment (McNeel Plugin Grasshopper), to identify changes in acoustic behaviour as response to variations of the system geometry (Figure 5, a and b).

These generative form variations went through a subsequent acoustic simulation (ODEON), taking into account a deflected shape of spheres in which the centre point of the dome is shifted. This was done in order to establish visual references for the relationship between manipulations of geometry, and the resulting acoustic behaviour. This second acoustic simulation was run using the optimised stage position originated from the results of the first analysis (with sound centre based in...
largest dome, configuration as spherical shape, centre equidistant to circumference). The results show the ideal dome with a steady state high sound concentration in a small area and uneven sound distribution across the entire audience area, and a deflected dome (Figure 6) with a centre of sphere to an elliptical shape, which shows level variations across the audience area as smaller, thus providing a better coverage of the entire audience area – a better acoustic performance.

To quantify the acoustic variations, sound pressure level (SPL\textsubscript{A}) is used as a descriptor of level across the audience area and Speech Transmission Index (STI) (Steeneken and Houtgast, 1980) is used to quantify speech intelligibility across the audience area for both configurations (Figure 7). In the original domes, speech intelligibility is high in the areas where the sound concentration happens, and diminishes closer to the enclosing walls, resulting in unacceptable speech intelligibility at several locations. In the deflected dome, an overall increase in speech intelligibility as well as an even distribution of sound level across the audience area can be seen.

Furthermore, this shape supports even distribution of reflections across the audience area. By bringing the back wall closer to the performer, useful reflections arriving at an early stage aid in raising the speech intelligibility across the audience area. A summary of the results for the original and warped dome configurations (Figure 8) is presented as numerical data, which shows the overall tendency of the results, as well as the distribution across the area. In the STI results, the warped dome configuration shows clearly that STI values are higher overall, and that the distribution is centred around a higher mean. The SPL results show that the occurrences in a certain histogram bin have a higher count, representing the even response in level across the audience area.

The extended acoustic analysis thus confirmed that specific characteristic of deflected curvatures in the intersecting spheres of the competition design resulted in good acoustic conditions, as opposed to a more classical approach of standard
ellipsoid spheres. Sound concentration in curved surface geometries can be further be managed in a micro topography (adapting direction, scale and smoothness of reflective segments), but in this case, the iterative interdisciplinary exchange confirmed that performance was significantly informed by the macro topography of overall surface geometry (adapting heights, position of centre points, dimension and curvature).

7. Conclusion

The paper has discussed a design solution to the problem of sound concentration in complex curved surfaces; by improving the acoustic behaviour through redirection of reflected sound. Through implementation of an interdisciplinary and iterative exchange between areas commonly separated through steps in the design process, better speech intelligibility and enhanced acoustic performance could not only be taken into account at an early stage, but moreover the intersection between computational design, structural analysis and acoustic simulation solved the problem sound concentration in complex curved geometry to such an extend as to support the preferred design decisions.

The paper introduced an iterative design, analysis and optimization processes, in which a number of generative form variations were developed in computational 3d modelling software (McNeel Rhino), variations developed as rule-based (Grasshopper), tested in engineering software (Strand7), and evaluated in acoustic simulation (ODEON). The investigation revealed that the structural deflection of original spherical geometry, and resulting sound reflection in relation to curvature of the space enhances the acoustic performance of the space. The design communication between disciplines enabled us thus to identify both the acoustically best positions for sound production (stage area) and acoustic experience (audience area), and it validated a geometry without relying on secondary absorption or
amplification measures. While curved surfaces are not usually recommended for performance spaces, the integration of generative design, structural and acoustic analysis provided good acoustic results by a deeper understanding of relationships between structure, space and sound.

In that manner, the final design solution carefully balances a diversity of requirements, from external force impacts, to interior sound fields. By interlinking knowledge, methodologies, expertise and software of different design realms, an open system is generated in which communications and transfers between team design and collaborative approaches are combined and inform each other.

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References