NOT PEER-REVIEWED

Commentary

Programming frictional squeaking at soft-rigid interface by geometric control

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Abstract

Frictional squeaking at soft-rigid interfaces is familiar, but the interfacial events that organize audible sound in extended contacts have remained difficult to identify. In a

recent *Nature* study, Djellouli *et al.* combine high-speed contact imaging with acoustic measurements to show that rapid opening slip pulses organize the sound. Surface ridges act as waveguides that confine pulse propagation, allowing the pulse repetition rate to lock to the first shear mode of the soft block and thereby set the acoustic pitch. These findings establish a structure-driven framework connecting surface geometry, interfacial rupture and acoustic pitch, offering a route toward friction regulation in engineering applications spanning transportation and geotechnics.

MAIN TEXT

When rubber-soled shoes slide on a smooth floor or a rubber conveyor belt slips, soft-rigid frictional contacts often emit sharp squeaking sounds [Figure 1A]. Such sounds are commonly associated with friction-induced vibrations, especially stick-slip oscillations in rigid or lubricated contacts[1]. Traditional interpretations have attributed such sound primarily to friction-induced stick-slip oscillations, as demonstrated in systems such as water-lubricated rubber seals[2]. In soft-rigid contacts, however, sliding may also proceed through localized detachment or opening slip pulses that travel along the interface[3]. When these pulses repeat at audible frequencies, they provide a plausible interfacial route from frictional rupture to sound. Such familiar squeaking highlights a ubiquitous contact configuration in soft-material systems[4], namely the soft-rigid frictional interface. Yet how an extended soft-rigid interface selects a stable pulse frequency and converts it into acoustic radiation has remained unresolved.

More than 50 years ago, dry sliding between rubber and glass was shown to proceed intermittently through detachment waves propagating along the contact interface, now known as Schallamach waves[5]. These waves mediate local separation and reattachment during sliding and are typically slow, with dynamics controlled by interfacial adhesion and viscoelastic deformation. By contrast, more recent studies of bimaterial friction have shown that interfacial rupture can localize into rapid opening slip pulses governed mainly by elasticity and inertia[6]. Such pulses can travel near the shear-wave speed of the soft material and repeat at frequencies within the audible range. They therefore provide a mechanistic bridge between localized interfacial rupture and frictional squeaking.

In their *Nature* study[7], Djellouli *et al.* directly connected sound measurements with high-speed images of the contact interface. Their results demonstrated that squeaking was closely tied to rapidly propagating opening slip pulses. Starting from a shoe-on-glass experiment, they recorded the acoustic signal while imaging the spatiotemporal evolution of interfacial contact. The ridged surface of the shoe generated rapidly propagating opening pulse trains whose repetition frequency closely matched the fundamental frequency of the acoustic signal, revealing a strong correspondence between interfacial pulse trains and the emitted sound. To identify the interfacial conditions for squeaking, they next compared elastomer blocks with controlled surface geometries. Flat blocks produced disordered pulses and broadband acoustic emissions, whereas ridged blocks produced regular pulse trains and a distinct squeak [Figure 1B]. Contact-area images further revealed that opening pulses in ridged samples were confined within individual ridges and propagated regularly along their length, whereas those in flat samples showed disordered nucleation, morphology and trajectories. A single sufficiently narrow ridge was enough to guide the pulses and generate a clear frequency peak. Together, these observations identify ridges as quasi-one-dimensional waveguides for opening slip pulses. Crucially, these pulses propagated at nearly the shear wave speed of the soft material, indicating that they were rapid, localized interfacial opening events governed by elasticity and inertia rather than classical stick-slip friction.

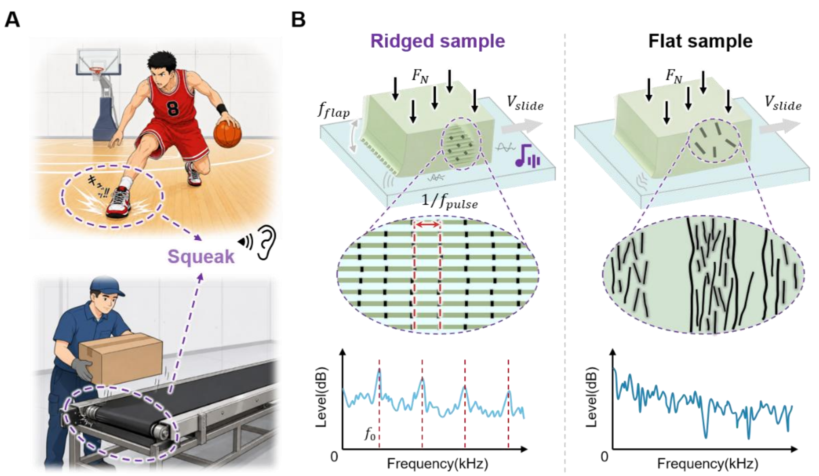

Figure 1. Surface ridges organize frictional squeaking at soft-rigid interfaces. (A) Everyday soft-rigid contacts, such as rubber-soled shoes on a floor and rubber conveyor belts, can emit sharp squeaking sounds; (B) Ridges confine opening slip pulses into regular pulse trains with a distinct acoustic frequency, whereas flat contacts allow disordered pulse paths and broadband acoustic emissions.

Djellouli *et al.* found that, as the ridged sample slid, its trailing edge periodically lifted, locally reducing contact pressure and triggering pulse nucleation, while its oscillation frequency matched the opening-pulse repetition rate. This indicated that pulse nucleation was coupled to periodic trailing-edge lifting, where transient reduction of normal contact pressure may lower the barrier for local interfacial opening and promote pulse initiation. Combined with theoretical estimations and numerical simulations, the authors further showed that both frequencies followed the first shear-mode scaling of the block. Ridges do not create a new bulk mode; instead, they suppress competing pulse paths so that the existing first shear mode dominates. Since the pulse repetition rate closely matched the fundamental frequency, the soft block's first shear mode set the fundamental frequency of frictional squeaking. Consistently, experiments showed that the measured fundamental frequency was consistent with the natural frequency of the first shear mode of an ideal elastic block, $f_0 = c_s/2H$, where c_s was the shear wave speed of the soft block and H was the block height. To illustrate this tunability, the authors used ridged samples with different heights to generate preselected squeak pitches. When slid across glass, these samples produced different musical notes and even "played" music, demonstrating that squeaking can be predicted and tuned.

Although geometric confinement provides a compelling explanation for the onset and frequency selection of squeaking, its robustness in practical material systems remains to be established. Variations in material stiffness, viscoelastic dissipation and frictional heating can alter pulse speed and modal response, thereby affecting the acoustic amplitude and stability of squeaking. Establishing how geometric confinement interacts with intrinsic material properties is therefore central to developing a predictive understanding of frictional squeaking at soft-rigid interfaces. Moreover, a central next step is to connect the spatiotemporal evolution of interfacial tractions to far-field acoustic pressure. In particular, synchronized measurements of contact area, tangential traction, normal traction and sound would reveal how a single pulse redistributes stress and radiates acoustic energy. This direct evidence is needed to establish how transient changes in interfacial shear and normal tractions are converted into far-field sound pressure[8].

Beyond geometric confinement, interfacial physics introduces additional complexity. Local adhesion at soft-rigid interfaces can significantly modify the nucleation threshold by coupling normal contact pressure and tangential traction, suggesting that pulse nucleation likely results from coupled effects of adhesion and frictional instability. Moreover, external environmental conditions, such as ambient humidity, adsorbed water layers and surface contamination, may alter the interfacial rheology and frictional response[9,10], and could therefore act as possible modifiers of the nucleation threshold and propagation speed of opening pulses. Systematic investigation is needed to disentangle the respective contributions of geometric confinement, material dynamics and interfacial chemistry to the acoustic response. It would further clarify how viscoelastic dissipation interacts with these factors. In particular, the mechanism by which opening pulses convert interfacial mechanical energy into squeaking sound remains unresolved, highlighting the need for synchronized spatiotemporal measurements of interfacial forces, contact evolution and acoustic emission.

By linking sound measurements with high-speed contact imaging, Djellouli *et al.* show that squeaking at soft-rigid interfaces can be understood as a geometry-selected interfacial rupture process rather than as an uncontrolled by-product of friction. Surface ridges guide opening slip pulses along prescribed paths and suppress competing pulse trajectories, allowing the pulse repetition rate to lock to the first shear mode of the soft block. In this way, ridge confinement transforms disordered, broadband frictional noise into regular pulse trains with a tunable acoustic response. The study provides a surface-geometry strategy for engineering soft contacts, with potential relevance to quieter seals, low-noise conveyor belts and tunable acoustic interfaces. More broadly, it shows that frictional interfaces need not remain passive sources of dissipation and noise, but can function as programmable dynamical systems. The next challenge is to determine how geometric control competes with material dissipation, adhesion and transient traction fields in engineering contacts.

DECLARATIONS

Authors' contributions

Proposed and designed the comment: Zhang WL, Duan, A;

Prepared the figures and wrote the article: Duan A, Gong L;

Revised and corrected article: Gong L, Wei ZY, Tian Y;

Supervised the manuscript: Zhang WL, Tian Y;

All authors have read the manuscript and approved the final version.

Availability of data and materials

Not applicable.

AI and AI-assisted Tools Statement

AI and AI-assisted technologies have been only used for improving its readability and language.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Consent for publication

Not applicable.

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