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EXPERIMENTAL ACTIVE CONTROL OF AUTOMOTIVE DISC BRAKE ROTOR SQUEAL USING DITHER

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This paper presents an experimental investigation into the application of "dither" control for the active control and suppression of automobile disc brake squeal. Dither control is characterized by the application of a control effort at a frequency higher than the disturbance to be controlled. In the particular system considered here, a vibro-acoustic analysis of a disc brake system during squeal determined the acoustic squeal signature to be emanating from the brake rotor. This squeal was eliminated, and could even be prevented from occurring, through the application of a harmonic force with a frequency higher than the squeal frequency. The harmonic force was generated by a stack of piezoelectric elements placed within the brake's caliper piston. The harmonic force represented a small variation about the mean clamping force exerted by the brake upon the rotor. The high-frequency vibration in the brake system due to the action of the control system was not heard if an ultrasonic control frequency was used. More importantly, the active control system is shown to be able to prevent squeal from even occurring. This gives rise to a possible active control system integrated into the brake system of automobiles to prevent squeal.

1. INTRODUCTION

The focus of the paper at hand is the presentation of a hypothesis-driven experimental investigation of active control of automotive disk brake squeal. Specifically, we hypothesized that dither control could suppress, or even prevent, brake squeal from occurring. In the following paragraphs, we briefly introduce the relevant art concerning dither and brake squeal. We then proceed to describe the dither control system employed here, and, finally, present the results of the experiments themselves.

Dither control refers to the use of a high-frequency, low-amplitude signal to modify the characteristics of a system (high frequency is here used in the sense of relative to the frequency of some response that is to be controlled). Often dither is used in non-linear systems to stabilize self-excited oscillations. It has been used in a variety of different applications including optics, image processing, controls, and communications to improve performance [1]. It is particularly useful in systems hampered by static friction or stiction, since it is thought to keep frictional interfaces slightly slipping at all times. Under certain assumptions and for certain system models, it is possible to demonstrate that dither effectively averages the non-linear self-oscillations [2–4]. Although dither has been widely used in a variety of systems and applications, its use for the suppression of brake squeal has not been reported, to the authors' knowledge.

A key aspect of dither control is that there is no requirement upon its frequency other than it must be higher than the friction-induced response frequency that one wishes to

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suppress. For example, available theory does not require that the dither frequency be a harmonic of the response, nor that it corresponds to the resonance frequency of some higher order mode, etc. Fundamentally, then, the choice of dither frequency is arbitrary, so long as it is greater than the frequency of the disturbance to be suppressed. Further, dither control is considered to be open-loop [2]. Consequently, these factors simplify the implementation of dither control systems, as there need not be sophisticated controllers, sensors, feedback loops, digital processors, etc. Indeed, all that is required to implement dither control is the means to generate a high-frequency signal of sufficient amplitude and to impose that signal upon the system of interest during times when friction is expected to be present and its effects are to be controlled. In the context of dither control applied to brake squeal, one need only know that the brakes have been applied, and use that as the criteria for activating the dither controller. Rather simplistically, the brake-light switch on all automobiles could be used to activate the dither controller, as well.

When dither is employed, as the input dither amplitude is increased, the system exhibits forced oscillations both at the dither frequency as well as at the undesired frequency. Depending on the nature of the non-linearity of the system, other sum- and difference-frequencies of the disturbance and the dither may be exhibited. Once the dither amplitude passes some threshold, what is termed "synchronization" occurs and limit cycles are extinguished. Once synchronization occurs, the system exhibits forced oscillations only at the dither frequency [2]. It is the authors' opinion, at present, that suitable analytical models for brake squeal do not yet exist that will permit application of the available dither control analysis methods. For example, analytical formulation of dither control as applied to brake systems will depend upon the friction model and the contact stiffness model, both of which are still under investigation. Nonetheless, the lack of a brake-specific analytical explanation does not preclude experimental investigation of the concept.

Turning now to how dither control itself relates to automotive brake squeal, consider that most researchers characterize brake squeal as a "self-excited vibration of the brake rotor, which is heavily related to the vibration behavior of the brake components and the friction variation between the pads and rotor" [5]. The component that is excited into vibration acts as a speaker, radiating sound as it vibrates. The brake rotor is one of the brake components that tend to develop resonant modes during squeal, as reported by Ichiba and Nagasawa [6] and Fieldhouse and Newcomb [7].

Many researchers over the years have studied brake squeal to determine causes of brake squeal. Many methods of measuring brake squeal parameters have been used, such as modal analysis of separate brake system components to characterize their natural frequencies, finite element analysis, acoustic holography, sound intensity analyses, and laser vibrometer analyses of squealing brake systems. Examples of such studies may be found in the literature [5–16]. A common squeal mechanism, discussed in references [8, 16], is the so-called "stick–slip" phenomenon between the brake pads and rotor. The "stick–slip" phenomenon has been shown to cause an out-of-plane vibration of a stationary object contacting a moving object by Sakamoto [17]. Given that brake squeal appears to be a non-linear friction-induced phenomenon, it rather naturally falls into the realm of dither control as a means of controlling it.

While dither represents a method for actively controlling brake squeal, passive means are available, as well. A great deal of research [5–16] has shown that brake components exhibit high magnitude of vibration during squeal, including out-of-plane motion of the brake pads on the rotor. Consequently, significant attention has been paid to the effects of damping the out-of-plane vibrations through viscoelastic material added to the back of the brake pads. The viscoelastic components have been referred to as "noise insulators" or "noise damping shims". Noise damping shims as a method of brake squeal control is widely known in the automotive industry, as explained by Sing *et al.* [18] and Heppes [19].

In addition to the passive control methods just described, other work has investigated active control methods. Nishizawa *et al.* [20, 21] developed what was termed an electronically controlled disc brake noise canceling system. This system involved a fully active feedback control. The feedback control system detected the out-of-plane vibration of the rotor and then applied a normal vibration to the rotor 180° out of phase to reduce the amplitude of the rotor vibration. The system was implemented on a four-piston disc brake (two pistons per pad). Piezoelectric elements were attached to each of the four brake pistons. Two elements were used to detect the vibration of the rotor and the other two were used to apply a vibration to the rotor from the control circuit. The system worked effectively both in the lab and during on-road tests. As compared to dither control, however, the Nishizawa's system applied its control effort at the same frequency as the squeal. Furthermore, Nishizawa's system is a full feedback control system, with all of the complexity that such system entails.

The key concepts that motivate the work at hand evident from the above review of the art are: (1) brake squeal is evidently a non-linear friction-induced limit cycle phenomenon, and (2) dither control has been demonstrated to suppress friction-induced limit cycle oscillations. It is therefore a natural extension to pose the hypothesis that dither control may be used to suppress brake squeal. The work at hand documents the results of an experimental program designed to test this hypothesis. In the following sections, we introduce the means whereby we introduce a dither signal into an example automotive disk brake system, as well as the experiment methodology used to test the efficacy of dither. We then provide the results for a number of dither trails, and draw conclusions.

2. DISK BRAKE DITHER CONTROL SYSTEM

Dither control requires the use of an actuator to impose a fluctuating force upon the system of interest. The system of interest for the experiments documented here was a single piston floating caliper brake system, acting on a 27·43 cm diameter ventilated rotor. A dither control actuator was integrated into the piston caliper, as depicted in Figure 1. The actuator was a 12·5 mm diameter, 25 mm long multi-layer piezoceramic (PZT) stack. The actuator was positioned inside the piston with one end in contact with the inboard brake pad and the other end contacting the closed end of the caliper piston. Means were provided at each end of the stack to center it within the piston, and to ensure that only

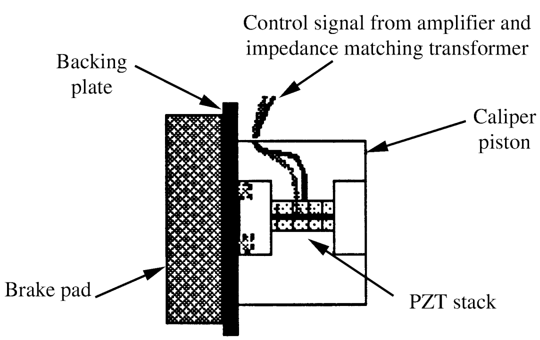

Figure 1. PZT actuator inside caliper piston.

axially loads were imposed upon it. This configuration produces fluctuations in the normal component of the brake clamping force. Fluctuations in the normal force perforce induce fluctuations in the friction force.

Generation of the signal to drive the actuator required the use of a function generator, a power amplifier, and an impedance matching transformer. The signal input to the power amplifier was generated using a function generator capability in a control program written using LabView. The power amplifier was a Crown Micro-Tech 2400 audio amplifier. The output of the power amplifier was routed through a Krohn-Hite MT-56R impedance matching transformer. The impedance matching transformer is required in order to provide greater power transfer between the amplifier and the capacitive load of the PZT stack. The output of the impedance matching transformer was wired to the actuator.

3. EXPERIMENTAL METHODS

The disc brake was installed on a brake squeal dynamometer. The dynamometer system had the capability to maintain a fixed rotation speed of the rotor, as well as controlling the brake line hydraulic pressure [13]. Thermocouples inserted into the brake pads were used to monitor pad temperatures. To determine the effect and the effectiveness of the control, the vibration of the brake system was measured with a Polytec scanning laser vibrometer, while the sound pressure from the brake system was measured with a calibrated precision microphone. The microphone was positioned approximately 0·61 m from the front of the outboard surface of the brake rotor. The vibrometer provided the capability to generate frequency-dependent images of the surface normal velocity.

Two basic procedures were employed of the work presented here. The first procedure required that the brake be brought into a condition of squeal, and then the dither control system was activated. The amplifier gain was increased until the squeal was suppressed. This procedure was used to establish the threshold level for squeal suppression. In the second procedure, the dither control system was activated at a level known to suppress squeal *before* the brake was applied. The system was then brought to the conditions that would normally generate squeal in the absence of dither, held in that state for a period of time, and then the control system was turned off. This procedure was used to assess if dither would prevent squeal from occurring.

For each of the basic procedures described above, selection of the dither control frequency was required. As noted previously, the selection of the dither frequency is constrained only in that it must be greater than the frequency of the response to be controlled. While we have performed tests for many more dither control frequencies than are documented here [22], for purposes of illustration we present here results for four chosen dither frequencies: 7·5, 16, 16·8 and 20 kHz. These frequencies are above the 5·6 kHz squeal frequency, as required. The 16·8 kHz control was selected as it represents a harmonic of the 5·6 kHz squeal, and we desired to investigate whether selecting a harmonic of the squeal would have any bearing upon the control efficacy. Finally, the 20 kHz tone was selected based upon the desire to have the dither-induced response beyond the range of human hearing (recall that the tradeoff in dither control is that while the response at the squeal frequency is suppressed, the system exhibits forced oscillations at the dither frequency. If the dither frequency is within the range of human hearing, dither suppresses the pure tone squeal at the cost of generating an audible pure tone dither noise).

The brake system used in this work exhibited but one squeal that could be repeatedly, reliably generated. This squeal was used for all of the experiments documented in this paper.

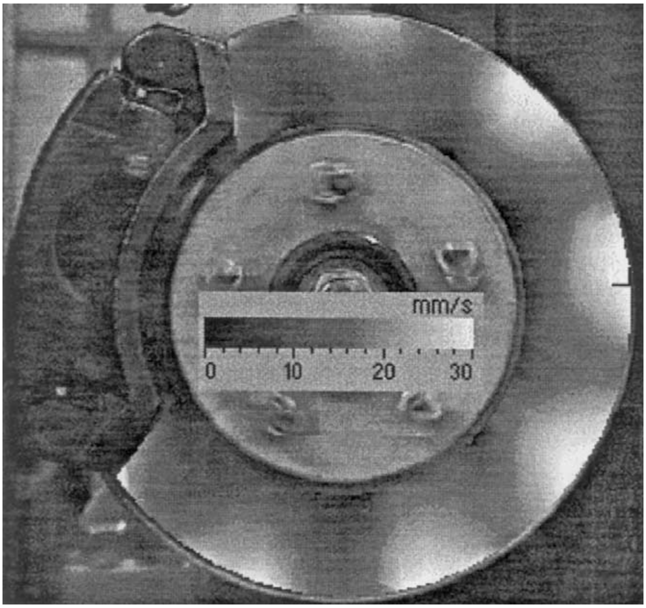

Figure 2. Rotor vibration at 5·6 kHz while in squeal at 5·6kHz.

While other squeals were sometimes excited, they were not consistent enough nor repeatable to the extent of being able to conduct controlled experiments against them.

The squeal condition used in the work at hand was produced for a rotor speed equivalent to a vehicle speed of 3·5 miles/h, a brake line pressure of 0·414 MPa, and initially ambient temperature of the brake pads. This squeal consisted of a single intense tone nominally at 5·6 kHz. Figure 2 presents a scan of the surface normal velocity of the exposed outboard rotor surface at 5·6 kHz while the brake was in squeal at 5·6 kHz. In Figure 2, the image of the vibration response has been superimposed onto an image of the rotor, and the scale and other notations have been digitally inserted into sections of the image that do not contain response data. The light gray areas periodically spaced around the circumference of the rotor represent the areas of greatest surface normal velocity. Figure 2 indicates that the rotor was vibrating in a mode when the 5·6 kHz squeal was generated.

4. SQUEAL SUPPRESSION EXPERIMENTS

The 7·5kHz dither signal with an input voltage of 183·6 V r.m.s. to the PZT actuator suppressed a 92 dB sound pressure level squeal down to the laboratory's background noise level of approximately 55 dB at 5·6 kHz. This was a decrease of 37 dB in sound pressure level at the squeal frequency. The cost of suppressing the squeal was the generation of an audible response at the 7·5 kHz dither frequency. With the application of dither, the sound pressure level at 7·5 kHz was 83 dB, a 28 dB increase above the lab background noise.

The surface normal velocity of the brake rotor at 5·6 kHz with the 7·5 kHz control applied is shown in Figure 3. Visually comparing Figures 2 and 3, which represent surface velocity at the same frequency and to the same color scale, it is evident that the application of the 7·5 kHz dither signal has completely suppressed the rotor mode at 5·6 kHz. For a numerical comparison, the magnitude of the surface normal velocity of the rotor at

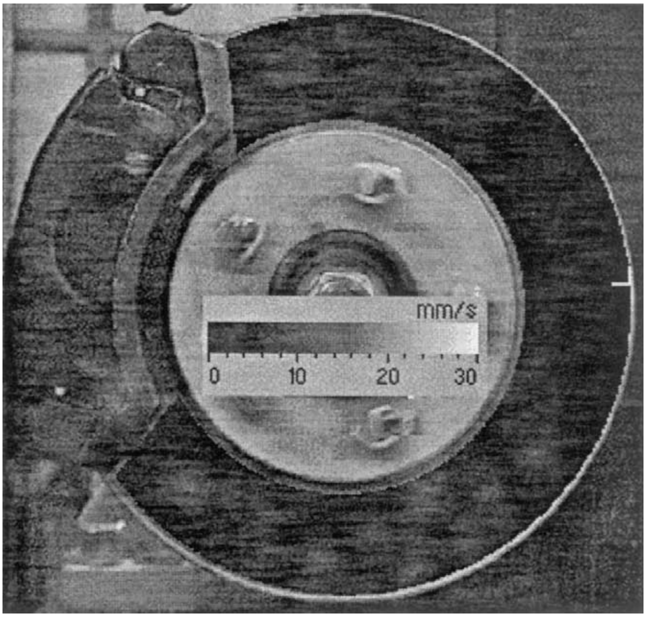

Figure 3. Rotor vibration at 5·6 kHz while 7·5 kHz dither signal applied.

a particular observation point during squeal was 34·62 mm/s. The magnitude of the surface normal velocity at that same point with the control system activated was 0·265 mm/s, indicating that the dither control system reduced the surface normal velocity of the rotor by a factor of 130 at the squeal frequency. As might be expected from the noted acoustic response at 7·5 kHz, the rotor vibration at this frequency increased. The surface normal velocity of the brake rotor at the 7·5 kHz control frequency is shown in Figure 4. The figure illustrates that the 7·5 kHz control signal induced a higher order mode in the rotor as compared to the original squeal response depicted in Figure 2.

The 16 kHz control signal also reduced the 92 dB squeal to the background noise level, but with an input voltage of 103·7 V r.m.s. to the actuator. The induced sound pressure level at the 16 kHz control signal frequency was 77 dB. Figure 5 indicates that the response of the rotor at 16 kHz does not exhibit a clear modal pattern. This test supports the contention that the dither signal need not correspond to the frequency of a mode of the brake system.

The 16·8 kHz control signal, which is 3 times the nominal squeal frequency, reduced the 92 dB squeal to the background noise level, a decrease of 37 dB, with an input voltage of 105·6 V r.m.s. The resulting noise level at 16·8 kHz increased from the lab background noise level to 83·5 dB, a 28·5 dB increase. The surface normal vibration of the brake rotor during the 16·8 kHz control is shown in Figure 6. As with Figure 4, Figure 6 evidences a higher mode of rotor vibration as compared to the squeal mode itself.

Finally, the 20 kHz control signal with an input voltage of 218·3 V r.m.s suppressed the sound level of the squeal to the background noise level. The resulting sound from the control signal was inaudible, unlike control signals of lower frequency, even though the resulting sound pressure level at 20 kHz increased to 85 dB. Figure 7 depicts the rotor response at 20 kHz with the 20 kHz signal applied.

As a footnote to the above results, those experienced in the field of brake squeal are aware that a given squeal frequency will tend to drift as the brake pads heat and wear: our system was subjected to the same variability. For the experiments we have performed, the

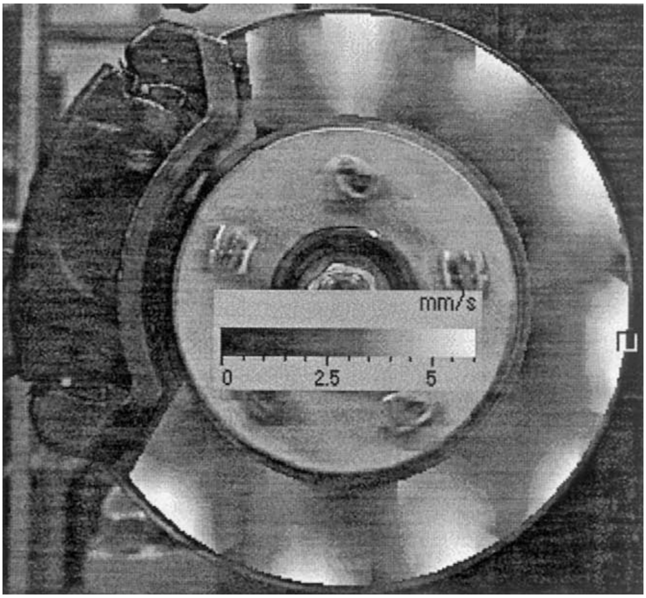

Figure 4. Rotor vibration at 7·5 kHz while 7·5 kHz dither signal applied.

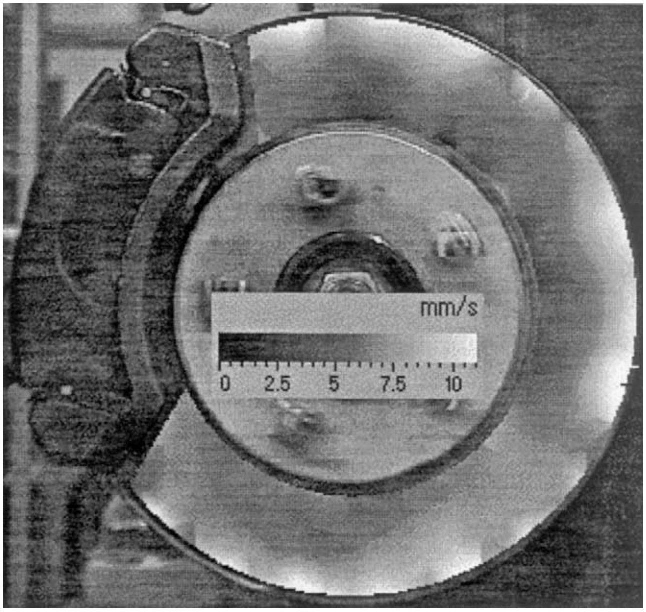

Figure 5. Rotor vibration at 16 kHz while 16 kHz dither signal applied.

frequency of the nominal 5·6 kHz rotor mode drifted down to 5·2 kHz at times, but the mode shape remained the same. Nonetheless, we did not have to adjust the dither amplitude or dither frequency as the squeal frequency drifted. This tends to imply that dither control as applied to brake squeal will be robust in the face of such variations, as the system need not compensate for them. Further, we have performed these tests at some 14 different dither

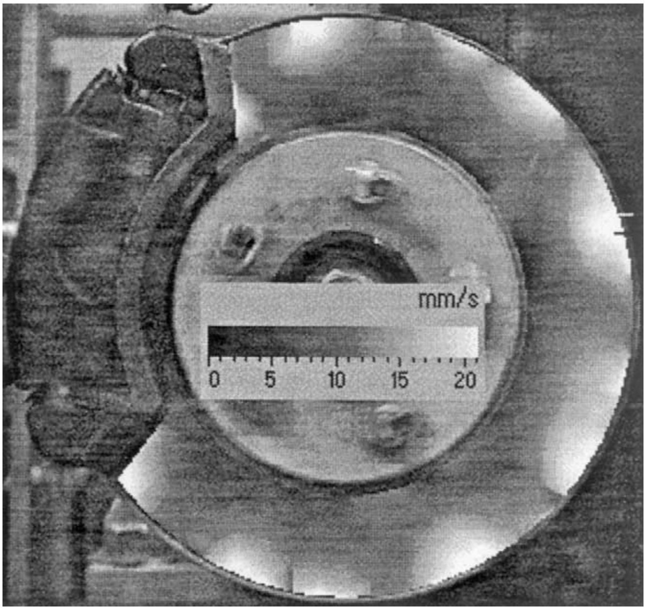

Figure 6. Rotor vibration at 16·8 kHz while 16·8 kHz dither signal applied.

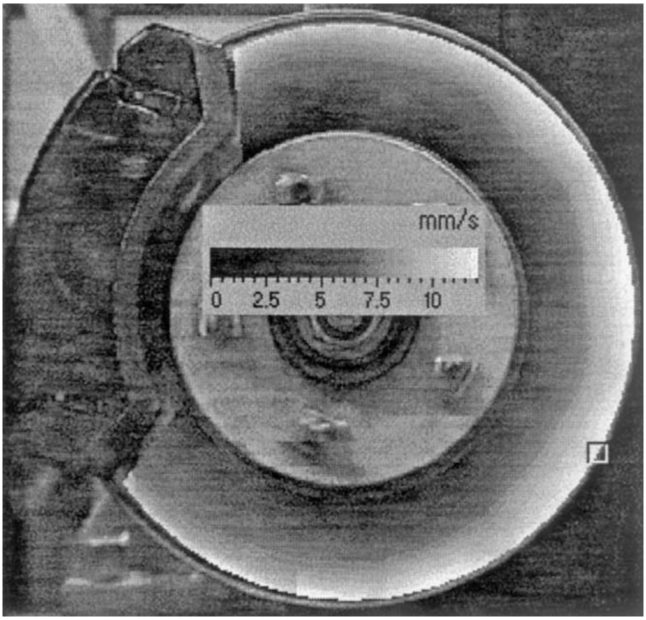

Figure 7. Rotor vibration at 20 kHz while 20 kHz dither signal applied.

frequencies (including those documented here), demonstrating effective control at each [22]. Once dither control has been established, the system has not exhibited evidence of sensitivity to dither frequency nor amplitude.

5. STAGES OF DITHER CONTROL

Brake squeal was not eliminated as soon as the control signals were activated. We observed that the noise level of the squeal gradually decreased as the amplitude of the control signal was increased. Both the control signal and squeal were detectable while the amplitude of the control signal was increased, but before squeal suppression. Finally, the squeal was totally eliminated when the control signal passed a threshold amplitude. This threshold behavior is termed synchronization, a characteristic of dither detailed in the literature [2–4]. These stages of dither control may be illustrated by considering the spectrum of the sound pressure level produced by the brake. For the 20 kHz dither control signal applied to suppress the 5·6 kHz squeal, time data were recorded during each of these stages, analyzed with the fast Fourier transform, and plotted.

Figure 8(a) is the sound pressure level spectrum during squeal but without dither control. The prominent spike at 5·6 kHz is the squeal tone. Note, however, that there are clear harmonics at 11·2 and 16·8 kHz as well, though these tones are some 20 dB down from the main tone at 5·6 kHz. A weaker third harmonic is present at 22·4 kHz, some 38 dB down from the fundamental. From a qualitative perspective, only the tone at 5·6 kHz was audible.

Figure 8(b) presents the sound pressure level spectrum after activation of the 20 kHz dither control signal at an amplitude of 75 V r.m.s. Synchronization has not yet occurred. The 5·6 kHz tone has been suppressed by 10 dB, the 11·2 kHz harmonic by 15 dB, while the harmonics at 16·8 and 22·4 kHz have been suppressed to the background noise level. In this example, the squeal tone was still audible, but not the control tone as it was beyond the range of human hearing.

Finally, Figure 8(c) depicts the sound pressure level spectrum once synchronization has occurred, at a control signal amplitude of 153 V r.m.s. Dither has suppressed the 5·6 kHz squeal and all of its harmonics. The only prominent tone remaining is that of the 20 kHz dither control signal. Again, since this dither signal is ultrasonic, it was not audible.

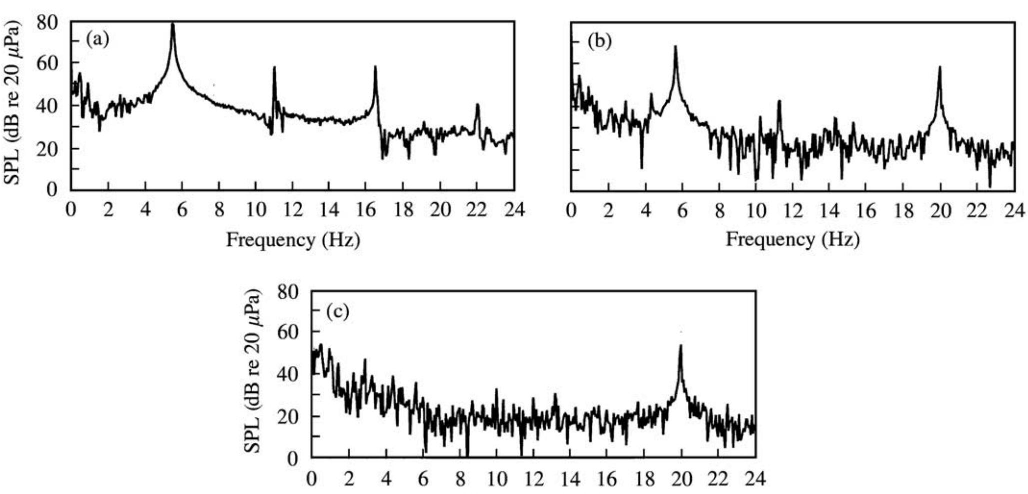

Figure 8. Sound pressure spectrum from the brake system during stages of 20 kHz control: (a) before control activation, (b) during partial control, (c) after synchronization.

6. BRAKE SQUEAL PREVENTION EXPERIMENTS

To investigate the ability of the system to prevent squeal from occurring, the control system was activated at the 20 kHz dither frequency and 214 V r.m.s. input amplitude, conditions known to suppress squeal, but while the brake was not yet in squeal. The brake system was subsequently brought into conditions that would normally generate squeal, by increasing the brake line pressure. The dither control system was cycled off, remained off for a few seconds, and then cycled back on again. Sound pressure level data were taken throughout this procedure. Figure 9 presents the results of this experiment, a spectrogarm of the sound pressure level versus time.

Throughout the time span represented in Figure 9, the brake system was in conditions that would otherwise have generated squeal. The control system was on for the first 4·5 s. The 20 kHz control signal was clearly effective in preventing squeal from occurring during this time. As soon as the control signal was turned off (at approximately 4·5 s) the brake squeal immediately returned. Once the control signal was activated again, at approximately 7·5 s, the squeal was suppressed. This experiment rather concisely demonstrates that dither control not only eliminates squeal, but prevents it as well. As the dither frequency for this experiment was 20 kHz, it was inaudible throughout the time that the system was in squeal.

7. CONCLUSIONS

The research presented in this paper showed that an experimentally designed active control system, using dither, was able to eliminate rotor-mode brake squeal, as well as

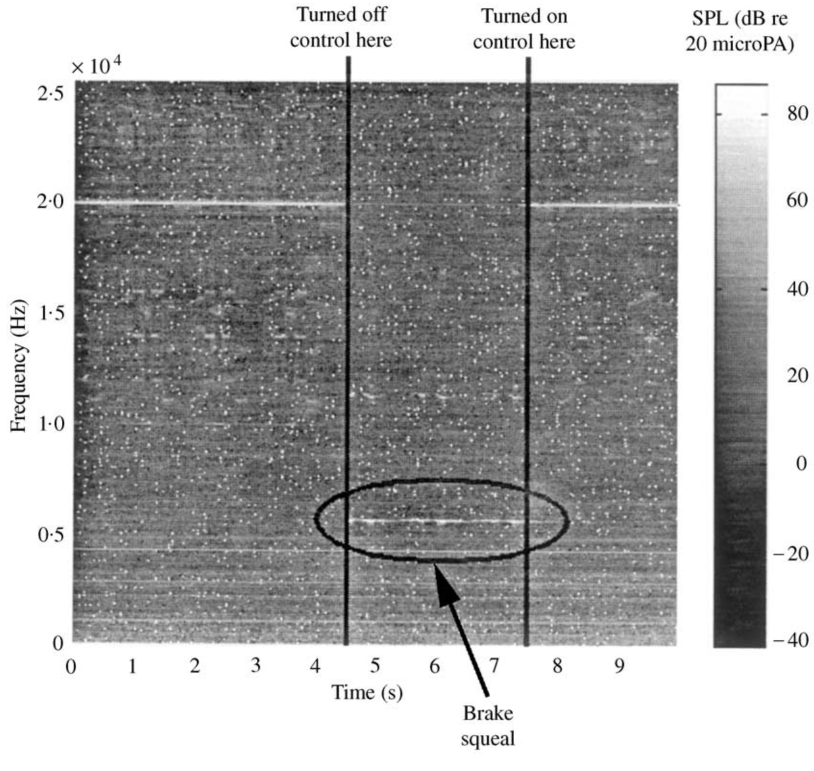

Figure 9. Spectrogram illustrating the prevention and elimination of brake squeal using a 20 kHz dither control signal.

prevent it from occurring. Even though the particular squeal mode would drift in frequency as the system heated and wore, this had no impact upon the control efficacy, nor did it require adjustment of the dither frequency.

We demonstrated that there was no particular requirement upon the selection of the dither control frequency. The dither control frequencies used here spanned from 7·5 up to 20 kHz. All were capable of suppressing squeal. Those dither signals that were within the range of human hearing produced an audible response at the dither frequency, an unavoidable consequence of the use of dither. However, the 20 kHz dither signal was beyond the range of human hearing, and as such, produced an inaudible response.

We demonstrated that the dither control system could prevent squeal from occurring. So long as the dither amplitude was high enough, brake squeal was not generated, but as soon as the control was deactivated, squeal appeared. The practical implication of this is that ultrasonic dither control, applied to the rotor before squeal conditions are reached, would prevent squeal as the brake pressure is increased to the squeal condition. Furthermore, the response at the dither frequency would not be audible during the braking application.

However, even though the results presented here are encouraging, we must qualify their generality. First, our brake system did not exhibit multiple simultaneous squeal modes, such that we cannot claim that dither control as implemented here would be effective against such a condition. Second, we have demonstrated that dither control as applied by our specific system is effective against rotor mode squeal: we have no evidence of its efficacy against other squeal generating components, such as pad tip flutter. Such is the focus of future work.

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