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Psychoacoustic Analysis of High Frequency Elasto-Acoustic Emissions from Hollow Driveshaft Tubes

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Abstract

Lightly damped non-linear systems such as vehicular drivelines undergo a plethora of Noise, Vibration and Harshness (NVH) problems. The clonk phenomenon is one concern which occurs as the result of impulsive torque input in the form of sudden clutch actuation or throttle tip-in and back-out. The resulting impact of meshing gear pairs propagate structural waves down the driveline. With lightly damped thin-walled tubes having high modal density, elasto-acoustic coupling occurs. High frequency noise emission is of metallic nature and quite disconcerting to vehicle occupants as well as passers-by. It is perceived as structural failure and/or poor-quality build. Therefore, the occurrence of the phenomenon is a concern to vehicle manufacturers and progressively constitutes a warranty concern. This paper investigates the clonk phenomenon through use of a long-wheel base rear drive light truck test rig. The investigation uses psychoacoustic metrics to establish the severity of clonk noise in different maneuvers. This is an attempt to quantify the effect of transient clonk event which is usually ascertained through subjective evaluation ratings in a customer/jury clinic in industry. Alternatively, detailed numerical analysis is carried out with parametric studies to quantify different clonk events, a very time consuming approach which is not usually correlated with occupants' perception of the event. Therefore, the experimental NVH monitoring-psycho-acoustic approach is new for the case of clonk and not hitherto reported in literature. The study corroborates the results and conclusions of previous work, pointing to the loudness and sharpness of high frequency short-lived "metallic" response, which is attuned to human aural perception. The psychoacoustic analysis has shown this to be as the result of short duration hard impact (accelerative period). This hard impact duration accounts for the bulk loudness and sharpness of the overall event. Therefore, effective palliation should focus on the attenuation of particular frequency bands, which carry the main contribution to loudness and sharpness.

Introduction

Fuel efficiency and reduced emissions are the key drivers in the development of modern powertrain systems. This trend has led to the concept of increased output power-to-weight ratio powertrain systems, which includes downsizing and light weight constructions. However, light weight structures are poorly damped and due to their flexibility possess a high modal density. This is particularly true of rear wheel drive vehicles' driveline systems with hollow thin-walled driveshaft tubes, typical of some trucks and vans. The result is a plethora of noise and vibration concerns, highlighted by Rahnejat [1]. In particular, any impulsive input, caused by abrupt throttle tip-in or back-out or sudden release of clutch pedal sends broad band structural waves onto the driveline system [2]. The driveline system response comprises low frequency rigid body motions, such as shuffle as well as high frequency structural modal behaviour as noted by Petri and Heidingsfeld [3] and Farshidianfar et al [4]. It is shown that with every cycle of driveline shuffle, there can be high frequency impacts in the various lash zones, a phenomenon referred to as clonk in industry [2-5]. The high frequency region of the clonk response coincides with the acoustic modes of the hollow driveshaft tubes, resulting in high frequency noise propagation [2, 6-8].

The root causes of the clonk phenomenon is investigated in detail by Gnanakumarr et al [8-10] and Turnbull et al [11] through combined rig-based experimentation and numerical analysis with application of impulsive action through sudden release of clutch. This causes impact of meshing gear teeth pairs of the transmission system, where a structural wave propagates from the impact sites onto the driveline of a long wheel-base rear wheel drive's hollow driveshaft tubes.

Clonk is a phenomenon which ranges from 300-5000 Hz. It is shown that the short duration hard impact of the order of few milliseconds induces broad band structural waves (500-4000 Hz) which excite the high modal density response of driveshaft tubes. The combined flexural torsional-bending responses of the tubes in the frequency band of 1000-5000 Hz correspond to the effective resonating modes of tubes' cavities in the form of breathing modes. This coincidence of structural and acoustic modes was shown to be responsible for the disconcerting metallic-type noise propagation. No structural damage is noted with the clonk phenomenon, which is essentially an elasto-acoustic phenomenon. However, the human aural sensibilities are particularly attuned to high frequency sharp noises, even of a very short-lived duration. Consequently in industry, clonk is considered as a failure state, because vehicle driver and occupants often perceive the same and at least regard it as a poor quality build. Therefore, various palliative measures are used in industry to mitigate clonk. These include wire-wound driveshaft tubes as vibration absorbers or foam-filling of the same as noise retardants [1, 12], which are only marginally effective and have untoward implications; costly and time-consuming in the case of the former and reactive and potentially carcinogenic in the case of the latter. Other potential palliative measures include the use of dual mass flywheel (DMF) [13, 14], which is used to counter transmission rattle, another major noise, vibration and harshness (NVH) concern in powertrain systems. However, studies by Gnanakumarr et al [15] showed that whilst DMF is the device of choice for attenuating rattle, its effect on overall noise reduction in hard impact duration of the clonk signal was by a mere 3 dB (a peak reduction from 109 dB to 106 dB). The effect of DMF on noise reduction was seen as global, whilst the use of friction-fitted sound adsorbent cardboard liners into hollow driveshaft tubes was localised and more effective, even with the use of a single mass flywheel. The cardboard liners effectively reduced the sharpness of all the high frequency spectral components as well as down-shifting the high frequency natural modes of the driveshaft tubes [15, 16]. These contributions reduce the sharpness and loudness of the system response, which are important in human psychoacoustics.

Average human hearing ranges between 20 Hz-20000 KHz [17] and is particularly sensitive to the 2000 – 4000 Hz range [ISO 226-2003]. Additionally, human aural perception is particularly attuned to the loudness and sharpness of the sound [18]. Two psychoacoustic metrics; loudness and sharpness, have been used to provide a novel insight into and a greater understanding of the severity of clonk under different driving conditions. Loudness is a measure of the sound strength, measured in sones. A sound must increase in intensity by an order of magnitude for it to be perceived as twice as loud [18]. Zwicker's loudness was standardised in DIN 45631, which uses a first third octave spectrum to calculate the loudness patterns [19]. This approach was used by Vafaei et al [12] to ensure that rig-based clutch-induced clonk (the approach used in this paper) correlated well with the on-road clonk response. Sharpness is a measure of the high frequency content in a sound, where a sharpness of 1 acum is a narrow band around a given centre frequency (at 60 dB level). There are several sharpness measures, notably the Aures sharpness [20], which is the only method incorporating the influence of absolute loudness on the perception of sharpness. This makes it more suitable for the analysis of clonk noise. Therefore, palliation of clonk should optimally be in line with human psychoacoustics.

The current paper aims to contribute to the evolving knowledge in the use of psychoacoustic metrics; loudness and sharpness, in classification of elasto-acoustic response of powertrain systems under impulsive conditions. As the first step it is important to ascertain the effectiveness of these metrics in classifying the severity of clonk response.

Experimental Measurements

Experimental test rigs are considered to be the optimum means of evaluation of elasto-acoustic response of driveline systems as they allow uninterrupted access to system components. Such a test rig was reported by Vafaei et al [12] which correlated well with vehicle conditions under clutch-induced clonk. A variant of the same test rig, using a 3-piece driveline system is used in the current study with the addition of a DMF, which is used in most light trucks [11] (Figure 1). The rig is driven by a 4-pole, 22 kW power electric motor with an IMO programmable inverter control. The transmission is engaged in various gears to ascertain the acoustic response of the driveshaft pieces at given operating conditions (i.e. torques and speeds). An accelerometer is placed on the clutch pedal to monitor the clutch release characteristics, when abrupt release of the clutch is undertaken. Abrupt release of clutch in 100-300 ms represents impetuous side-slipping off the clutch pedal by the driver, leading to impulsive input to the driveline system, and resulting in clonk conditions. This has been determined through exhaustive vehicle road tests. A 2-beam laser Doppler vibrometer faces the driveshaft tube of interest, with a free field microphone placed at an appropriate distance on the opposite side of the same driveshaft tube. In the current study the focus is put upon the microphone-monitored sound pressure response as this is the necessary signal for any subsequent psychoacoustic analysis.

Loudness is the human subjective perception of the sound pressure level monitored by the free field microphone. Unlike the sound pressure level as a physical quantity, the perceived loudness comprises physical, physiological and even psychological attributes. Zwicker's Loudness [19], embodied in DIN 45631 (ISO 532B) standard, provides equal-loudness (in phons) line graphs which are functions of frequency and sound pressure level:

$$Loudness, S = 2^{\frac{L_p - 40}{10}} \quad (1)$$

where the loudness is in sones and the sound pressure, L_p in phons. Since the human auditory system is frequency-dependent, the procedure highlighted here is extended to integrate the sound pressure level with frequency content of the stimulus, leading to the establishment of the equal-loudness line graphs [19].

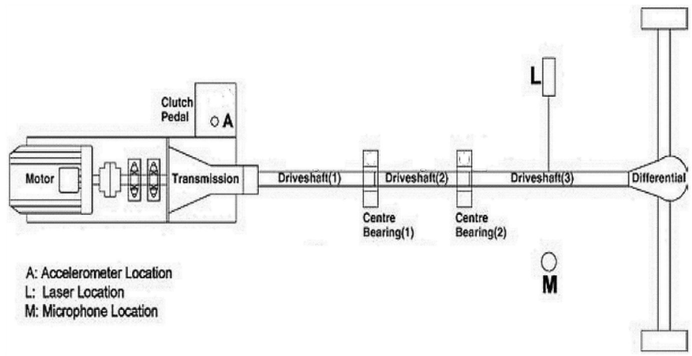

Figure 1. The powertrain clutch-induced clonk rig (after Theodossiades et al [14])

Results are obtained for a number of operating speeds, representative of the normal operation of the powertrain system used. These correspond to an electric motor-supplied power in the range 5-50 Hz in increments of 5 Hz for different selected gears. The motor frequency of 25 Hz corresponds to an input transmission shaft speed of 1500 rpm with an applied torque of 145 Nm, when engaged in 2nd gear; the worst clonk conditions. This paper focuses on further analysing this condition.

Results & Discussion

Figure 2 shows a typical clonk noise signal, in this case for a transmission input shaft of 1500 rpm with an applied torque of 145 Nm, when engaged in 2nd gear. It comprises of a number of distinct regions. With the release of the clutch the lash in the transmission gearing, universal cardan joints and splines in the driveline system are taken up. This accounts for the short ramp up of sound radiation from any of the hollow thin-walled driveshaft tubes, followed by the hard impact in any of the lash zones. The accelerative response occurs as the result of the short-lived hard impact. The severity of the structural wave from the impact sites reduces after the hard impact. Thereafter, the hollow driveshaft tubes promote reverberation in the form of ringing noise at lower acoustic modes of their cavities.

Power Spectral Density (PSD) is used to evaluate the frequency content present in each part of the clonk event signal. In addition to the problem of aliasing, another commonly associated problem with spectral analysis techniques is spectral leakage. A digitally computed Fourier transform of finite record length signal inherently assumes that the signal is periodic [21]. When the acquired signal contains a number of whole periods (i.e. an integer number), the signal decomposition would be ideal. However, this is unlikely, as most samples are acquired in non-integer periods, leading to some discontinuities, which appear as frequencies in the Fourier spectrum, which are not actually present in the original signal. This phenomenon is known as spectral leakage [21, 22]. Windowing can reduce or eliminate spectral leakage as it essentially uses multiples of the sampled data by a function which diminishes at the end of any selected windowed record. This is beneficial as it transforms the non-integer period sample into one which contains an integer number of periods, thus eliminating spectral leakage. Windowing has the detrimental effect of reducing the power content of specific frequencies, this was combated through further implementation of a filter; which resulted in no diminishing effect. A digital Infinite Impulse Response (IIR) bandpass filter used was designed to filter out responses outside the range of interest, 300-5000 Hz. IIR filters are recursive filters which are considered most efficient when implementing digital signal processing. This is the approach used here.

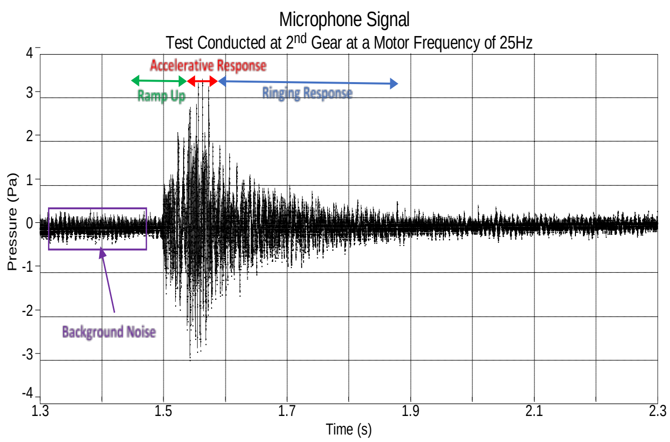

Figure 2. Clonk sound signal at transmission input shaft speed of 1500 RPM with applied torque of 145 Nm in 2nd gear.

The recorded sound pressures in Figure 2 are similar to those reported by previous studies using a variant of the same powertrain system [8, 9, 11] with peak values of approximately 3 Pa.

Using the aforementioned windowing and short power spectral techniques, Figure 3 shows the PSD of each of the 3 regions of the clonk signal (i.e. ramp-up, accelerative and decaying ringing noise regions). An important point to note is the broad band nature of the signal. Furthermore, the signal contains low and high frequency components, with increasing higher frequency contributions during the accelerative portion of the clonk response. The decaying ringing noise contains a higher proportion of lower frequencies. This is because there is less elastic wave energy to excite the higher acoustic modes of the driveshaft tubes. Human aural sensitivity is a function of frequency as noted on the equal-loudness graphs. It is most sensitive to the frequency range 2000 - 4000 Hz, thus more attuned to the propagated accelerative response during the hard impact. Numerical analysis reported by Turnbull et al [11] showed that the modal structural response of the driveshaft tubes correspond to their higher order combined torsional-bending modes, known as flexural breathing modes. These modes are efficient noise radiators, which coincide with their natural acoustic modes. Whilst this analysis explains the physical nature of clonk noise as measured by a microphone, a psychoacoustic analysis is required to ascertain the same for human perception.

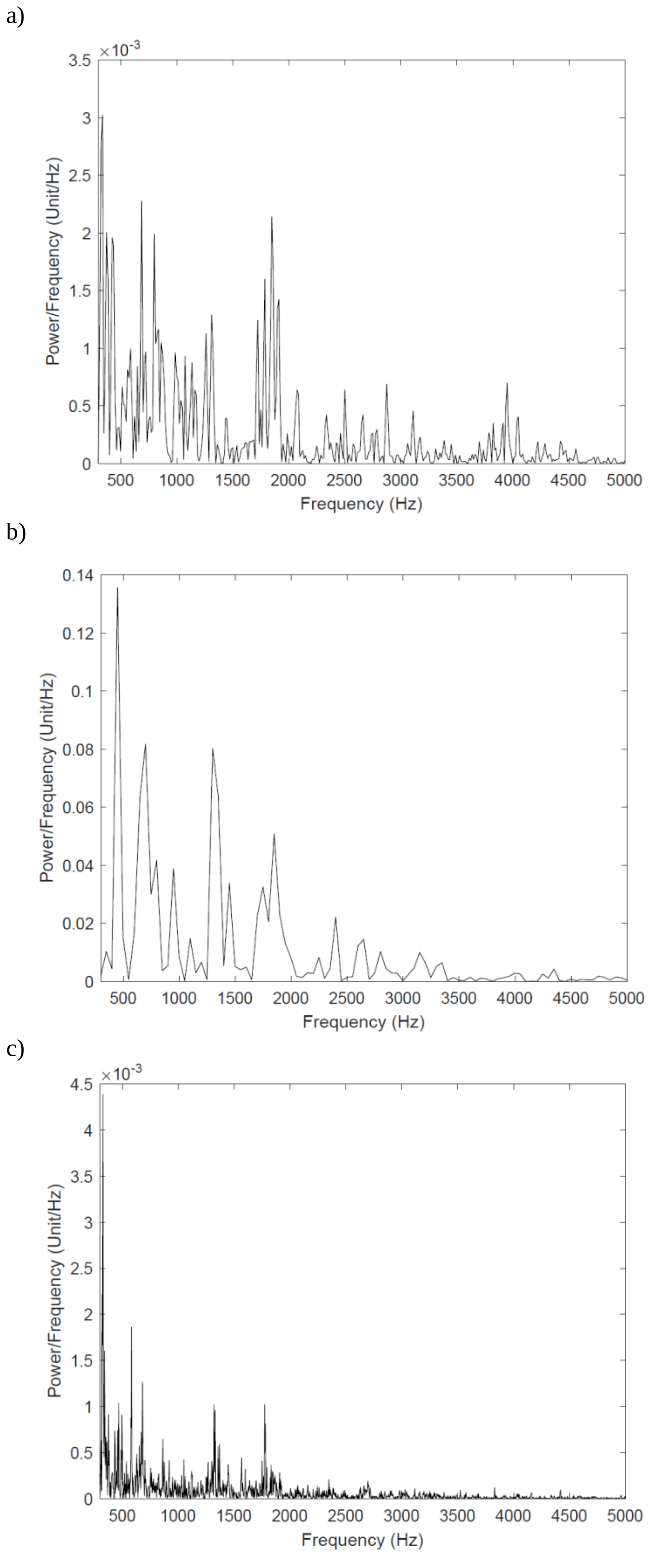

Figure 3. Power Spectral Density plots for (a) Ramp Up, (b) Accelerative and (c) Ringing/Decaying responses of a clonk signal at transmission input shaft speed of 1500 RPM with applied torque of 145 Nm in 2nd gear

Figures 4 and 5 show the psychoacoustic metrics; loudness and sharpness, for each of the three regions of the clonk noise signal in Figure 2. They also show their percentage with respect to the loudness of the overall signal. Figure 4 clearly demonstrates the loudness dominance of the accelerative noise (hard impact) region of the signal. It is approximately 50% higher than the overall signal loudness, thus poignantly perceived as noted by the rig operators during testing. The same is reported by vehicle occupants subject to the same driving conditions on a test track. In fact, the driving conditions pertaining to engine speed of 1500 rpm and 145 Nm applied torque in 2nd gear with hurried release of clutch pedal has been reported to be the worst discerned clonk response for the vehicle in question [8-11]. The current psychoacoustic analysis confirms this finding.

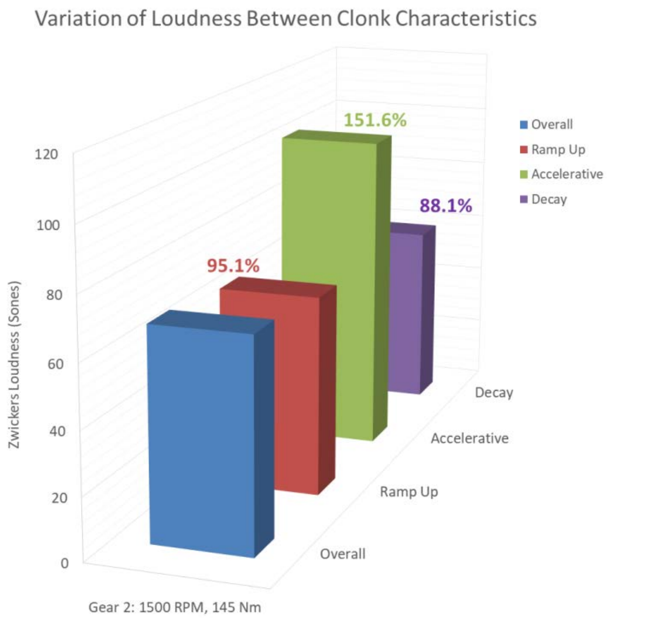

Figure 4. Bar chart representation of loudness in each region of a clonk signal with its percentage contribution to the overall loudness of the clonk event

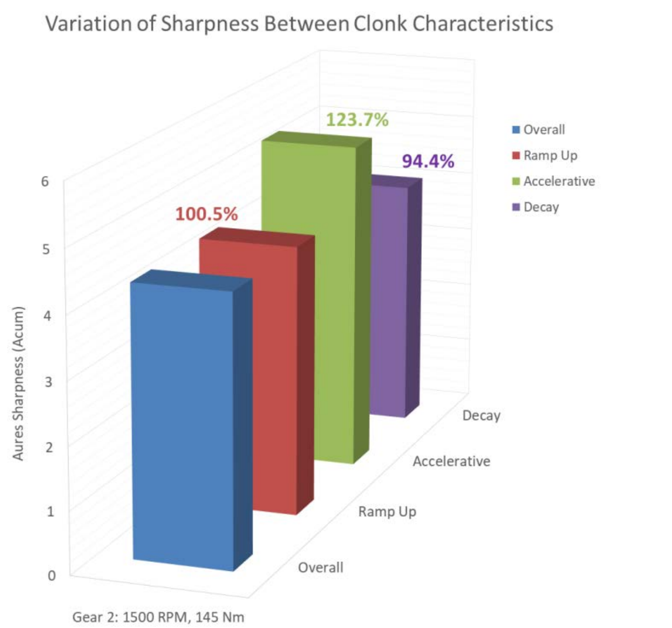

Figure 5. Bar chart representation of sharpness in each region of a clonk signal with its percentage contribution to the overall sharpness of the clonk event

It is important to note that aural perception averages the effect of sound pressure level over a period of approximately 0.1 s. For periods shorter than 0.1 s the sound would appear to be louder, stabilising around 1 s. Therefore, for shorter periods the sound perception is louder, meaning that the hard impact accelerative noise (15ms approx.) is more pronounced than the overall clonk response (45 ms) (Figure 2). Therefore, the effect of high frequency content is quite poignant.

Figure 5 shows the analysed results for the perceived sharpness of the propagated clonk noise. It can be seen that the sharpness of noise is nearly 25% higher in the region of accelerative noise. This sharpness accounts for the severity of loudness discerned for higher acoustic breathing modes of the driveshaft tubes at higher frequencies.

Conclusions

A psychoacoustic analysis has been long overdue when examining powertrain NVH concerns, particularly clonk. The present analysis confirms the findings of physical sound data obtained by the free field microphone and shows its conformance with the experiential data from human subjective ratings of the clonk phenomenon. It is interesting to note that the transient nature of high frequency (short-lived) event is captured by the psychoacoustic analysis. The analysis also shows that the poignant aspects of clonk occur in the mostly attuned frequency-dependent range 2000 – 4000 Hz. This is in line with all the previous microphone-based physical data. The implications of these findings are that effective palliative measures could reduce the sharpness of the accelerative response to the overall signal response (in this case by 20%). This would eliminate many suggested palliative measures, if the same overall thin-walled structures are to be retained. As the human aural perception declines from the frequency range 2000 - 4000 Hz, palliative solutions within this band of frequencies would be ideal. This finding points to the use of traditional solid driveshaft pieces with mainly rigid body motions and very high frequency flexure modes, a solution which is contrary to the current light-weight concept. Another solution may be the decoupling of structure and acoustic modes. In such a solution, tube ends may be furnished with low stiffness components to filter high frequency waves or baffles inserted into the tubes to break the path of wave propagation. Therefore, the psychoacoustic analysis reported here opens the way for the establishment of a quantifiable method for assessment of proposed palliative methods.

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Definitions/Abbreviations

NVH	Noise, Vibration and Harshness
DMF	Dual Mass Flywheel
PSD	Power Spectral Density