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ANALYSIS OF ACOUSTIC EMISSIONS FROM GAS ATOMISATION

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ABSTRACT

It is well known that during close-coupled gas atomization introduction of the melt into the gas stream affects the emitted noise. However, there has been virtually no study of this 'acoustic signature'. In this paper we present a quantitative comparison of this acoustic signature for an atomizer under gas only and gas + melt flow. We find that upon introduction of the melt there is strong absorption of frequencies in the 1-8 kHz range. These frequencies are characteristic of the resonance of droplets with 150-600 μm diameters and may be indicative of the dynamics of the initial breakup of melt ligaments. Moreover, during atomisation we find that there are considerable low frequency (< 30 Hz) fluctuations in the intensity of the acoustic emissions. We show this may be related to atomizer pulsation, the quasi-periodic low frequency variation in the melt volume instantaneously at the atomizer tip.

INTRODUCTION

Close-Coupled Gas Atomization (CCGA) is the technique of choice for the commercial production of fine (5-50 μm), highly spherical, metal powders such as might be utilised for Metal Injection Moulding (MIM) and Additive Layer Manufacturing (ALM). In principle CCGA is straightforward, high pressure gas jets impinging upon a molten metal stream are used to disrupt the stream, breaking it into a spray of fine droplets that then solidify in flight. However, the complex interaction between the high velocity gas and the metal results in a turbulent, and often chaotic, flow with the result being that the details of the process are far from well understood.

One of the most common manifestations of this complex interaction between the gas jets and the melt stream is atomizer pulsation. Commonly seen as a flickering of the luminosity of the atomisation spray cone, this is a short period variation in the amount of metal being instantaneously delivered to the atomisation tip.[1] During atomization, liquid metal is delivered down the central bore of the atomization nozzle, wherein it wets the nozzle tip (a process termed pre-filming, which is itself dependent upon the

gas flow conditions) and is stripped off the circumferential edge of the nozzle by the gas. The melt flow rate depends upon the pressure at the nozzle outlet, which in turn depends upon the dynamics of the gas flow. The application of high speed video analysis has been one of the key techniques in characterising and understanding the pulsation phenomenon.[2,3] Through such analysis a significant scientific literature has built up attributing these fluctuations to the transition between open- and closed-wake conditions as the melt flow alternately disrupts, and is disrupted by, the Mach disk formed by the recompression shock in the supersonic gas flow.[1,2] The formation of the Mach disk is in turn sensitive to the atomizing gas pressure[4], the design of the gas delivery manifold[5] and both the external[1] and internal[6] geometry of the melt delivery nozzle. It is postulated that this alternation between open- and closed-wake conditions leads to pressure fluctuations at the atomizer tip which drive the observed pulsation, although this remains controversial, with some authors[5,7] arguing that wake-closure is of no real consequence during two-fluid atomization. However, recently a more complex pulsation behaviour has been uncovered.[8] At low pressure, where the atomizer would be expected to only be in the open-wake condition, the temporal distribution of melt volume instantaneously at the atomizer tip follows a log-normal distribution. Conversely, at high pressure, the temporal distribution of the instantaneous melt flow-rate follows two superimposed log-normal distributions, one with a high flow-rate and low (geometric) standard deviation, the second with a lower flow-rate but higher standard deviation. In the high pressure case it is postulated that high-flow rate is associate with the atomizer being in the open-wake condition while the low flow-rate condition is associate with the atomizer switching to the closed-wake condition, with the system pulsing between the two states.[8]

From a production point of view melt pulsation is likely to be a significant problem due to the consequent variation in the instantaneous gas-to-metal ratio, *G*. Mullis *et al*.[3] used high speed video analysis to estimate the instantaneous melt flow-rate, from which the value of *G* was determined assuming uniform gas flow. This was found to vary between 1.26 (kg gas/kg metal) to 15.16 over a filming interval of < 4 s, compared with the time averaged value of *G*, measured from the gas and metal consumption rates, of 2.84. The typical frequency of the variation was < 20 Hz. As far as we are aware, no studies exist relating the instantaneous gas-to-metal ratio to the particle size produced. However, extensive data correlating median as-solidified particle size to the average gas-to-metal ratio[9,10] would suggest that high *G* is likely to correlate with small particles size and conversely low *G* with larger particle size. Consequently, significant short-period variation in *G* is likely to lead to substantial spread in the particle size distribution.

However, despite the advances in the understanding of the gas atomization process that high-speed video analysis has helped to bring about, there are very significant limitations as to its use. This is particularly the case if we wish to do this in a production, as opposed to purely research, environment. These may be listed as follows:

1) The high cost of the equipment means that very substantial capital investment is required,
2) Most commercial gas atomization systems have very limited viewing ports and the positioning of cameras can be difficult and intrusive upon plant operation, there is also a risk of damaging the high cost optics,
3) Very careful positioning and alignment of the optics is required in order to obtain good results,
4) The application of such techniques is limited to high melting point metals wherein the melt stream is visible via its own radiant light,
5) The size of the data stream is very large and consequently real time processing of the data is not feasible.

For these reasons, in this paper we present a preliminary investigation of an alternative technology which has the potential to yield the same (or richer) data about the performance of gas atomizers but which is low cost, less intrusive and much more robust, both in terms of the care required in setting up the equipment and its own resilience to damage. Experience with commercial gas atomizers is that they are

noisy (typically 100-110 dB at 1 m) and that the sound level is loudest in gas only flow, subsequently dropping (typically by 10-14 dB) on introduction of the melt. Moreover, there is also a change in the tone of the noise produced whereby an experienced operator can often tell when a system is operating optimally from the noise it produces. Both phenomena are thought to arise due to the absorption of acoustic energy by the melt, with individual droplets selectively absorbing frequencies close to their fundamental mode of vibration, which is given by Yule & Dunkley[11] as

$$\omega = \frac{4}{\pi}\sqrt{\frac{\sigma}{\rho_L D^3}} \qquad (1)$$

where σ is the surface tension of the melt, ρ_L the density of the melt and D is the droplet diameter. Indeed, this selective absorption of acoustic energy is used in both ultrasonic atomization and in the design of certain CCGA gas manifolds which include resonant cavities to promote frequencies corresponding to a desired particle size (e.g. the USGA[12] atomizer design). However, the proposition here is that this selective absorption of acoustic energy can be used to develop a relatively simple system to characterise atomizer performance by analysis of its acoustic signature, essentially automating and formalising the trained ear of an experienced operator. In contrast to high speed imaging, acoustic recording is inexpensive and can be setup at a distance of ~ 1 m from the atomizer, without the need for direct line-of-sight of the melt plume. Moreover, the equipment is much more robust than precision optics, needs no careful alignment and produces a data stream of a size that would make real-time processing feasible. The acoustic monitoring of industrial plant is already commonplace, particularly as a means of providing early warning of the impending failure of mechanical systems.[13]

DEVELOPMENT OF AN ACOUSTIC ANALYSIS METHODOLOGY

To illustrate the principal we have made an audio recording during gas atomization at the Sheffield plant of Atomizing System Ltd. (ASL). The gas atomizer studied uses a gas delivery die of the annular slit type with the melt delivery nozzle having an included apex angle of 30º, a tip diameter of 9 mm and a central bore for the melt feed of 5 mm. During the trial recorded here the atomizer was operating with nitrogen gas at a gas inlet pressure of 2.4 MPa. The melt and gas flow rates were 0.25 kg s^{-1} and 0.35 kg s^{-1} respectively and a typical batch atomization takes ~15 minutes, wherein some 200 kg of metal is atomized. During the run recorded the gas was pre-heated to an inlet temperature of 200 ºC, wherein the jet exit temperature upon ideal expansion will be -83 ºC. This compares to a jet temperature of -155 ºC without pre-heating of the gas.

The recording is 14:12 (mm:ss) in duration at a sampling rate of 44.1 kHz, giving ~ 37 M samples. The theoretical maximum frequency resolution at this sampling rate is 22.05 kHz. However, to avoid the introduction of artefacts when the sound being recorded contains frequencies higher than this, the recording apparatus was equipped with an anti-aliasing filter with a cut-off at 15 kHz. Figure 1 shows two short sequences of this recording at the start (Fig. 1a) and end (Fig. 1b) of the atomization process. Prior to the start of atomization there is some noise due to the induction heating system being used to melt the metal (i). The gas is introduced first leading to a sharp increase in the acoustic intensity (ii) followed, as expected, by a drop in intensity over the next 3 s or so as the metal is introduced (iii) and its flow attains steady-state (iv). In Fig. 1b we see the end of the steady-state period of melt flow (iv). As the melt is exhausted (v) the acoustic intensity increases reaching a maximum when the atomizer is in gas only flow (vi). Finally the noise level drops as the operator shuts off the gas supply (vii) with the final valve closure evident as a sharp spike in the intensity, followed by a lower intensity signal from the induction heater (viii) prior to this being shut down.

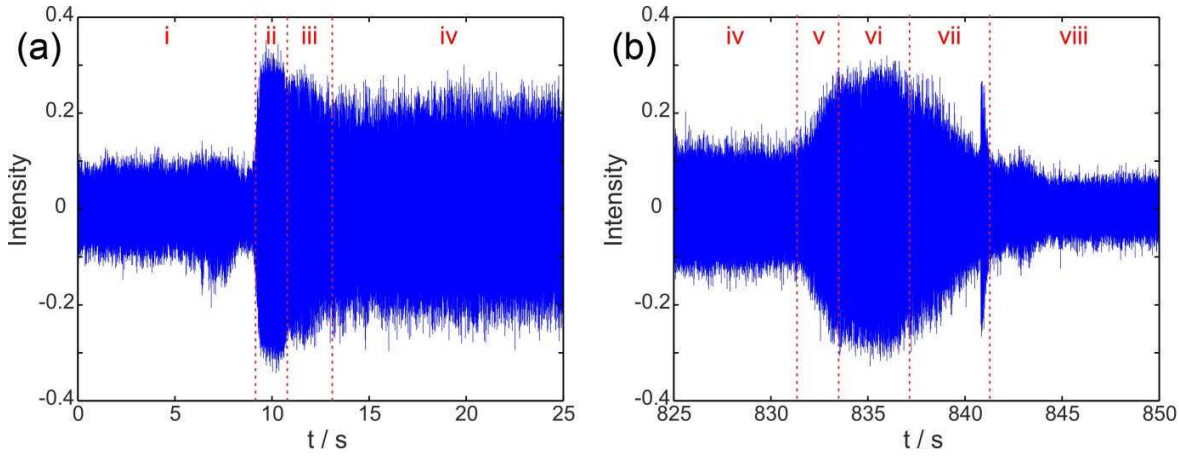

Figure 1. Two short sections of the waveform obtained from an audio recording of (a) the first 25 s and (b) the last 25 s of a gas atomization run. The regions identified are (i & viii) background noise from induction heating system, (ii) gas only noise prior to melt introduction, (iii) transient due to melt introduction, (iv) steady-state during atomization, (v) transient due to exhaustion of melt supply, (vi) gas only noise following exhaustion of melt supply, (vii) transient during shut-off of gas supply.

We can see from Fig. 1 that the introduction of the melt does indeed significantly reduce the intensity of the sound produced by the atomizer. It is a relatively small step to postulate that this behaviour is likely to be reflected in the instantaneous behaviour of the atomizer (i.e. that the atomizer is louder when there is less melt instantaneously at the atomization tip and quieter when more melt is present), wherein an amplitude modulation of the noise produced by the atomizer would arise from which atomizer pulsation can be monitored.

To assess any amplitude modulation of the acoustic signature we have applied standard signal processing techniques. The audio signal is first rectified (i.e. the negative half of the waveform is converted to positive) before a low-pass filter is applied which will recover the amplitude modulation without *a priori* knowledge of the frequency spectrum of the modulated wave. This process is shown schematically in Figure 2.

In these trials an infinite impulse response (IIR) filter was used. IIR filters are one of two primary types of digital filters used in Digital Signal Processing applications (the other type being finite impulse response, FIR). Unlike FIR filters, IIR filters have feedback (a recursive part of a filter) and typically meet a given set of specifications with a much lower filter order than a corresponding FIR. For a recursive IIR filter the n^{th} component of the filter output signal, $y(n)$, is given in terms of the filter input signal, $x(n)$, $x(n\text{-}1)$, $x(n\text{-}2)$ …, by

$$y(n) = \frac{1}{a_0}\left[\sum_{i=0}^{M_f} b_i x(n-i) - \sum_{i=0}^{M_b} a_i x(n-i)\right] \qquad (2)$$

where b_i are the feedforward filter coefficients and a_i are the feedback filter coefficients. Here the filter is of order M_f in the feedforward component and M_b in the feedback component.

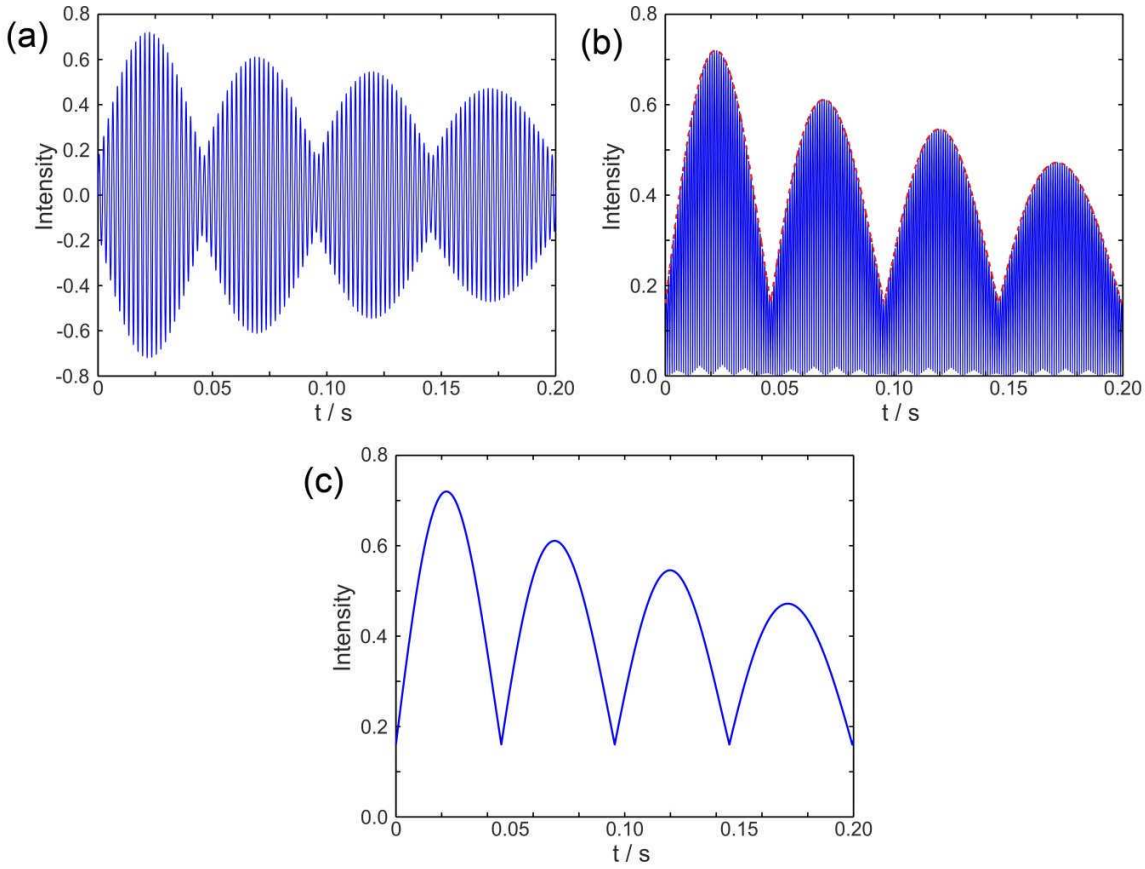

Figure 2. Schematic diagram showing the demodulation process, (a) sound wave with amplitude modulation, (b) rectified sound wave, (c) after passing through low-pass filter the original sound wave is removed and the modulation is recovered.

The particular filter used here was designed such that frequencies ≤ 40 Hz pass through unattenuated (gain = 1, or 0 db). For frequencies > 40 Hz the attenuation rises smoothly to -80 dB at a frequency of 100 Hz. This required a three section filter of order 11 in both M_f and M_b. However, for those unfamiliar with digital signal processing these details may be ignored. The frequency transfer characteristics of the filter are shown in Figure 3 and in essence the process is to apply the filter shown in Figure 3 to a rectified version of the sound recording, portions of which are shown in Figure 1. Low frequencies pass through unattenuated, while higher frequencies are very effectively blocked (-80 dB is a reduction by a factor of 10^8.)

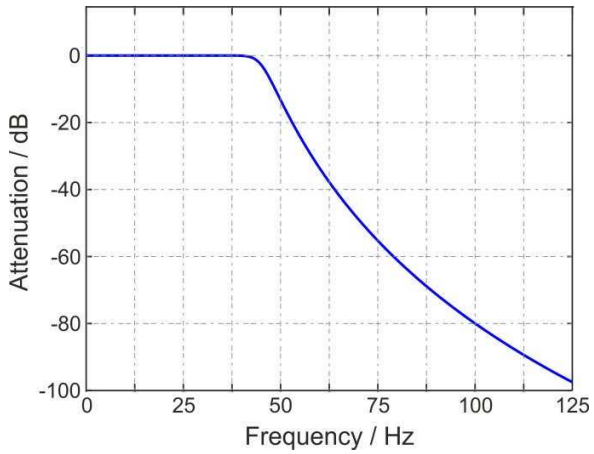

Figure 3. Frequency transfer characteristic of the IIR filter used in this work.

RESULTS - AMPLITUDE MODULATION ANALYSIS

Figure 4 shows a 4 s portion of the recording following signal processing to recover any amplitude modulation in the acoustic signal. The nature of the variation is qualitatively similar to that obtained using high speed imaging to measure the volume of melt instantaneously at the tip of the melt delivery nozzle (compare for instance Figure 4 here with Figure 3b in Ref. [8]), with the caveat that here low acoustic intensity will imply high melt flow-rate.

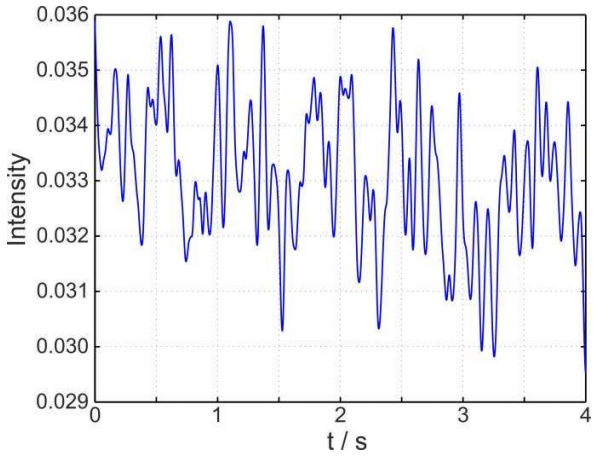

Figure 4. Result of applying amplitude de-modulation to a 4 s portion of the audio recording obtained during gas atomization (from region iv, gas + metal flow). Approximate 20% variation in the overall audio intensity of the signal is apparent during the 4s period shown.

However, to confirm the validity of the signal being recovered we have also tested the signal processing routine on samples of both uniform and Gaussian 'white noise'. From Mullis *et al.*[8] we have reason to believe that the temporal variation of the melt flow-rate has a log-normal variation. As such, a log-normal variation in the recovered audio signal would tended to confirm that it was mirroring the melt flow-rate, particularly if an identical analysis applied to 'white noise' does not produce such a trend. To this end filter output from both the atomizer recording and the 'white noise' sample have been subject to statistical analysis. In each case the time series data resulting from signal processing was converted to a cumulative frequency plot, wherein the distribution could be analysed. Six 25 s sample recovered from the audio

recording were analysed and in each case it was found that the intensity distribution could be approximated by a log-normal distribution, exactly as has been found to be the case with melt flow-rate data obtained from high speed imaging experiments[8]. The average skewness for the six samples was +0.18. In contrast the 'white noise' samples did not show this property, with the average skewness being -0.017 and +0.004 for the uniform and Gaussian samples respectively. Consequently, the 'white noise' samples could not be modelled as log-normal, appearing instead to be much closer to normal, rather than log-normal. That the signal recovered from the audio recording of gas atomization displayed a property that we know might be expected in atomizer pulsation (a log-normal distribution of intensities) and that this was not replicated by 'white noise' samples passed through an identical processing routine, gives confidence that the signal does indeed carry useful diagnostic information relating to the atomization process.

Above we have demonstrated that acoustic recording could in principle be used to obtain the same type of data as has previously been obtained using high speed imaging. However, there also appears scope to obtain information that cannot be obtained using high speed imaging. One of the limitations of high speed imaging is the relatively short recording time available due to the very large data sets generated. Mullis *et al*.[3,8] reported data based on 3.64 s of video recording (65536 frames at 18000 fps) and of necessity were unable to resolve features with a longer period than this. In contrast, in Figure 5 we present evidence for two apparently long period fluctuations. In the first (Fig 5a), which occurs within the first minute after the melt is introduced, we see two very distinct dips in the acoustic intensity. The origin of these fluctuations is uncertain but the proposed inverse correlation between melt flow rate and acoustic intensity would mean that these fluctuations correspond to a sudden increase in the melt flow rate that persists over a prolonged period. That these fluctuations occur soon after the introduction of the melt, but are not observed later on in the process, would seem to indicate that transient phenomena persist for much longer after atomization commences than has previously been realised. These could relate to a thermal instability during the initial thermal loading of the atomizer as the hot metal is introduced into the much cooler system or to the initial formation of a skull on the melt delivery nozzle. For the first of these fluctuations the duration is around 3 s with the interval between the pulses being 15 s. Given that the duration of high speed filming is typically no more than a few seconds, these are not features that would be readily apparent using such a technique.

In the second example (Fig. 5b), which in contrast was recorded towards the end of the atomization run, we see a very distinct oscillation with an average period around 12.5 s. This oscillation, which is observed throughout the second half of the atomization run, drifts in period between 10 – 15 s. Again, the origin of this pulsation is unclear, although we think it unlikely that fluctuations in the gas flow-field, such as the open- to closed-wake transition normally cited as the origin of atomizer pulsation, could operate with such a long period. One possible explanation, although this is yet to be verified, is that metal is periodically solidifying on to the tip of the melt delivery nozzle and then being broken-off by the gas jet. Such accretions are visible on the melt nozzle following atomization and tend to build up on the initially flat tip of the melt nozzle, elongating it further into the gas stream and creating a pointed, rather than flat tip. It is well known that the aspiration pressure is a sensitive function of the melt nozzle geometry so it would therefore not be surprising for changes in the melt nozzle geometry to lead to fluctuations in the melt flow rate. This would also explain why this particular long-period oscillation is only observed during the latter stages of the atomization process, when such accretions are more prevalent.

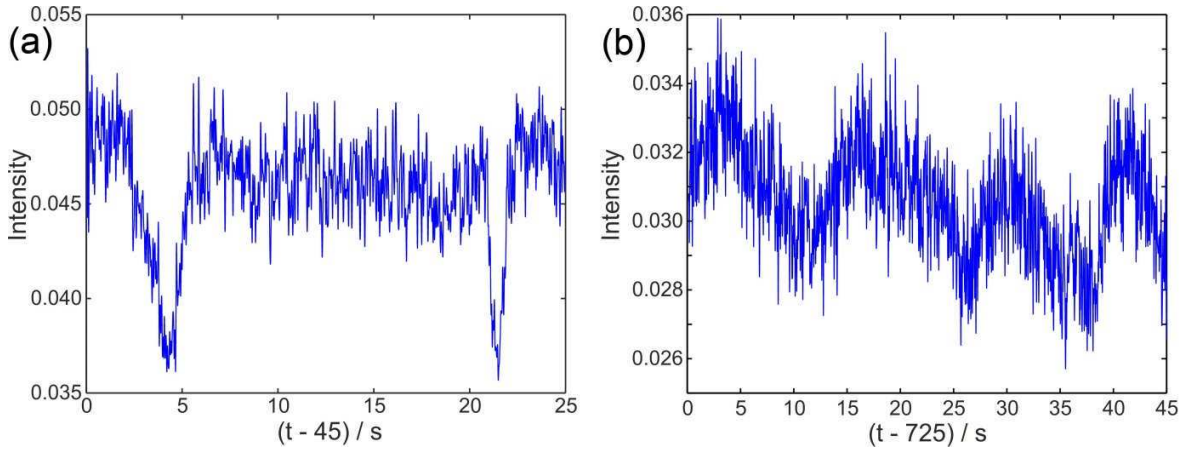

Figure 5. Long period fluctuations in the atomizer acoustic signature revealed by applying amplitude de-modulation. (a) Near the beginning of atomization two sudden drops in acoustic intensity (corresponding to pulses of increased melt volume) and (b) near the end of atomization a 10 – 15 s periodic fluctuation.

RESULTS - FREQUENCY ANALYSIS

As discussed above, the introduction of the melt to an atomizer can change not only the intensity of the emitted sound, but also its pitch. To demonstrate this we have taken the Fourier transform of two 3 s segments of the recording. One is of gas only noise and is taken from region (vi) in Figure 1b, the other is of the (gas + metal) noise and is taken from the middle of the atomization run. The individual frequency responses are shown in Figures 6 a & b respectively, while Figure 7 shows the ratio of the (gas + metal) to (gas only) noise.

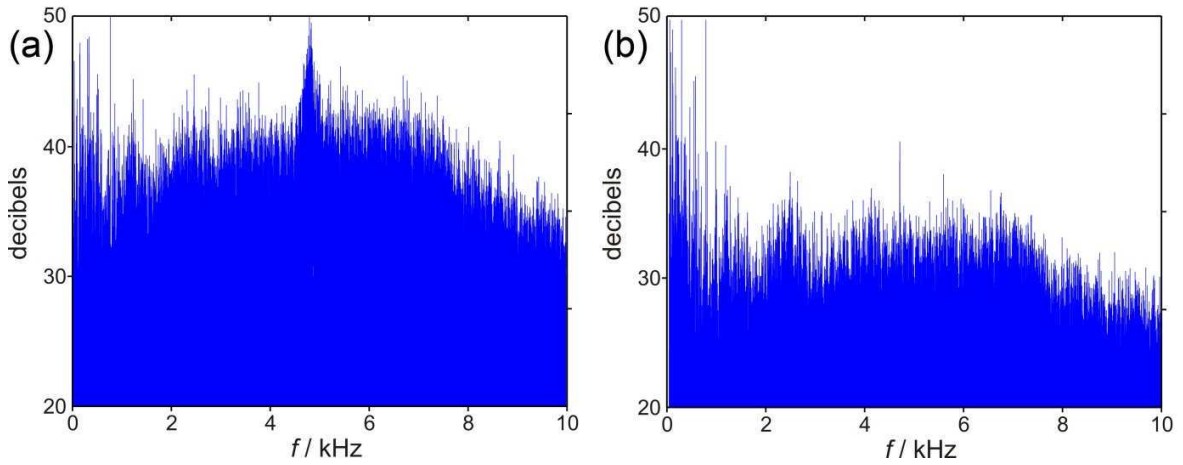

Figure 6. Fourier spectral analysis of two 3 s segments of the recording, (a) gas only noise taken from region vi towards the end of the recording following exhaustion of the metal supply and (b) from the middle of the steady-state atomization of the metal.

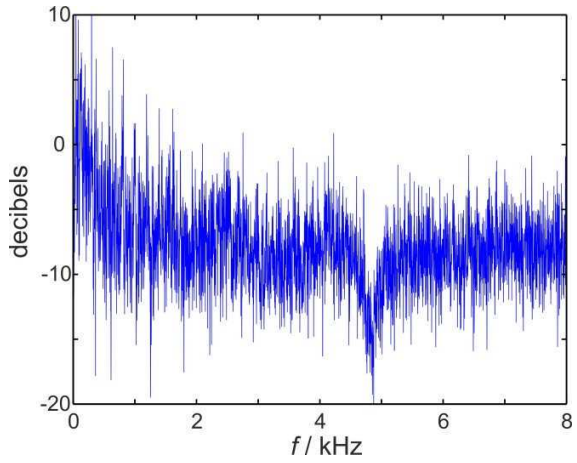

Figure 7. Ratio, as a function of frequency, of the (gas + metal) to gas only noise.

Upon introduction of the melt there is strong absorption of frequencies in the 1-8 kHz range, typically by around -7 dB relative to the signal for the gas only noise. These frequencies are characteristic of the resonance of droplets with 150-600 μm diameters and may be indicative of the dynamics of the initial breakup of melt ligaments. However, two regions are observed where this uniform 7 dB absorption is not evident. At low frequency (< 400 Hz) the (gas + metal) noise is greater than that of the gas only noise. These frequencies are too low to correspond to droplet breakup as described by Equation (1) and are probably an artefact. Perhaps of more interest is a sharp ~ 10 dB peak in the gas only noise at frequencies between 4.7-4.9 kHz, which is subsequently strongly attenuated in the (gas + metal) spectrum, this being evident in Figure 7 as a sharp dip in the ratio of the signals.

The origin of the 4.8 kHz peak in the gas only spectrum is unknown. For a jet temperature of -83 ºC the velocity of sound is ~ 275 m s^{-1}, wherein a resonance at 4.8 kHz would correspond to a wavelength of 5.7 cm, with the cavity generating this resonance being either 2.8 cm or 1.4 cm, depending upon whether it is a λ/2 or λ/4 resonance. No such cavity was engineered into the gas delivery die so we assume that this is a stray resonance. However, irrespective of the origin of the resonance, once the metal is introduced to the system the 4.8 kHz peak disappears, either because these frequencies are being absorbed during melt breakup or because the presence of the melt stream inhibits the 4.8 kHz resonance. We consider the former scenario the more likely, wherein Equation (1) predicts a particle size around 100-200 μm diameter, which is probably consistent with the particles formed in the primary atomization zone. Although further verification work is required, if acoustic monitoring were able to reveal information regarding particle size during primary jet breakup this would be a potentially valuable tool for in-line process monitoring during gas atomization.

SUMMARY AND FUTURE OUTLOOK

A preliminary analysis of an audio recording made during close-coupled gas atomization has revealed that such recordings could prove a valuable tool to study pulsation phenomena during atomization. Audio recording has the potential to allow such pulsation phenomena to be studied at much lower cost than current techniques, which generally involve filming the atomizer at high frame rates. Acoustic techniques are also much more robust and less intrusive on plant operation. However, a further and perhaps as yet unrecognised advantage, is that audio recording will allow the study of much longer period instabilities during atomizer operation. During this preliminary analysis two such were identified, including a quasi-periodic oscillation with period 10 – 15 s which develops several minutes into the atomization run and then persisted until the melt is exhausted.

However, it is also the case that the audio signal provides a less direct means of studying atomization than high speed video analysis. From a video analysis it is a relatively straightforward matter to estimate the volume of melt instantaneously at the atomizer tip. In contrast, in the audio signal, although evidence of atomizer pulsation is evident, it is not at all clear that a simple linear relationship between acoustic intensity and melt volume exists. Simultaneous high speed video and audio recording will allow the pulsations in the audio recording to be calibrated against the same pulsations in the video data such that the relationship between the audio signal and the instantaneous melt volume may be elucidated.

Preliminary evidence also indicates that Fourier analysis of the audio signature could yield useful information about the size of droplets present, particularly in the primary atomization zone and with regard to ligament break-up. This analysis could be extended using short-time Fourier transformations to produce a time-resolved frequency analysis (spectrograms) to determine whether pulsations in the acoustic amplitude were correlated with changes in the frequency spectrum of the acoustic signature of the atomizer. Such analysis could in principle yield information as to whether the dominant particle size being instantaneously produced was varying as a consequence of atomizer pulsation.

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