INVESTIGATION OF TORQUE FLUCTUATIONS IN EXTRUSION THROUGH MONITORING OF MOTOR VARIABLES

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Abstract – The extrusion process is highly prone to fluctuations in throughput and melt viscosity due to feed material variations and conveying, mixing, and thermal inefficiencies of the process. These fluctuations can result in poor product quality and higher scrap rates, hence early detection & diagnosis is important to minimize possible product defects and process inefficiencies. Usually extruders are equipped with melt pressure and temperature instrumentation at the latter stage of the process but not an overall picture of the process inside the barrel. Therefore, more advanced methods are required for early diagnosis of process fluctuations. Screw torque variations offer an integral measurement of the polymer state along the length of the extruder. Such measurements have the potential to yield earlier and more sensitive indication of process instability than measurements at the die. Strain gauges have been used to investigate dynamic torque signals in a specially-designed solids conveying device, but are not practical or cost-effective for retrofit in a production environment. Also, the installation of a torque sensor in between screw and motor shaft is not easily achievable due to several constraints. However, there is potential to track screw load torque dynamics through the analysis of extruder motor current and voltage signal variations. In this work, process fluctuations in extrusion are investigated by analysis of melt pressure and high frequency motor signals. Experimental studies were carried out to investigate process fluctuations with a virgin and a recycled material under different operating conditions. The estimated torque signal is shown to be a useful complement to pressure measurement in the identification and diagnosis of process issues.

Introduction

Extruder screw load torque variations have been shown to provide good insight to process fluctuations in extrusion [1,2]. In particular, screw torque/power can reflect high frequency (above the screw rotation rate) changes in the melt properties and throughput [2]. As an integral measurement of the polymer state along the length of the extruder it also has the potential to give an earlier and more sensitive indication of process instability than measurements at the die. However, few workers have attempted to analyse screw load torque measurements to observe process fluctuations. That is mainly because of the practical difficulties of installing and maintaining dynamic torque measuring devices in an industrial environment. Direct measurement of screw load torque involves installation of a torque sensor on the machine to measure the dynamic screw torque as screw rotates. In the case of rotary torque sensors, the sensor must be attached between the extruder motor shaft and screw shaft, allowing the sensor to rotate with the screw. Strain-gauge sensors have to be placed on the screw. Both types are difficult to retrofit in industrial extruders.

Some modern extruders have torque sensors built-in (mostly by placing strain gauges on the screw shaft), but these are relatively rare. Also, several manufactures display screw torque signals estimated from extruder motor signals provided by electrical sensors. However, Eker et al., [2] argue that standard torque signals provided in extruder control electronics are highly filtered due to the presence of noise and cannot provide information at the frequencies required.

Derezinski [1] measured screw dynamic torque of a 63.5mm extruder with a wheatstone strain-gauge bridge attached to the screw between the drive and flow channel. Melt pressure and torque signals were observed for different types and forms of resins (i.e. powder or pellet). Results revealed that the dynamic torque of each resin depended on screw speed and barrel set temperatures particularly in the feed zone. The amplitude of torque signals increased as screw speed increased and barrel temperature decreased. He proposes that the low frequency torque fluctuations are due to mis-match of melting rate with the rate of screw rotation, which results in solid bed break up. The high-frequency torque oscillations are independent of speed and temperature, but dependent on polymer. Furthermore, he proposes that high frequency oscillations are due to solid conveying and frictional effects. The frequency variations of the torque signal...
appear to be a function of the polymer and not a function of the resin form (pellets or powder).

Menning [3] used a single screw extruder with a specially designed barrel, instrumented with strain gauges, to measure local torque gradients along the conveying, melting, and metering zones of the barrel. Three torque sensors were mounted on the extruder barrel: two at the beginning and end of the feed zone, and another at the end of the melting zone. Pressure transducers were also mounted along the barrel to monitor the pressure gradient along the channel. The results obtained from two materials show that torque inside the screw barrel in a particular zone for a given drag flow depends on the pressure gradient in that particular zone and particularly on its sign. The highest torque level was observed at the beginning of the feed zone and torque level reduces gradually along the subsequent zones of the screw. However, torque gradient and level are likely to depend on the material. How torque variations relate to process stability was not explored.

Indirect measurements of screw load torque can be achieved by observing the extruder motor electrical variables. Eker et al., [2] proposed an observer technique to estimate extrusion screw torque from motor electrical variables. They verified the observer performance only through simulations and were not implemented on an actual plant. The method proposed only applies to induction motor drives (a.c. motors). In fact, most industrial extruders use d.c. motor drives.

Frequency analysis of process signals has been shown to provide information about process problems. Becker et al., [4,5] describe frequency analysis of measured process signals as a useful tool of studying the stability of the extrusion process, particularly with regard to the appearance of the extrudate surface. Melt pressure at the die and along the barrel was measured for three different materials under different processing conditions and a number of conclusions and predictions were made based on spectral analysis together with visual observations of extrudate: machine vibrations directly affect the flow stability and unstable melting of the resin along the screw resulted in an increase in noise level. They also postulated that the shape of the frequency spectrum related to the frequency of the extrudate surface distortions.

In this study, motor electrical variables are used to estimate d.c. motor torque during processing of a virgin and recycled HDPE. Analysis of the magnitude and frequency spectra of the estimated signals is carried out to investigate the processing behaviour of materials under different conditions.

**Experimental**

**Theory**

The motor torque, $T_m$, of a d.c. motor is given by a linear function of armature current (motor with constant field) or a combination of both armature current and field currents (motors with separate field excitation).

$$T_m = K_f I_f + I_a$$  \hspace{1cm} (1)

Where, $K_f$ and $K_t$ are the motor torque and field constants respectively, $I_f$ is the field current, and $I_a$ is the armature current (for a constant field motor with $K_f I_f = 1$).

**Fig. 1: Block diagram of a plant with a variable field d.c. motor**

The block diagram of an extruder plant with separately excited motor is shown in Figure 1 (for a constant field motor the $K_f I_f$ input to the motor torque can be ignored).

The power provided to the screw by a d.c. motor, $P_{sc}$, is given by:

$$P_{sc} = \eta T_m N \omega_{sc}$$  \hspace{1cm} (2)

where $\eta$ is the efficiency of the gear box, and $N$ is the gear ratio, and $\omega_{sc}$ is the screw speed. Gear box efficiency is a constant for a specific speed of the motor and $N$ is a constant for a particular machine. This must be equal to the power consumed by the screw in rotating the load, this is equal to:

$$T_L \omega_{sc} = \eta T_m N \omega_{sc}$$  \hspace{1cm} (3)

$$T_L = \eta T_m N$$  \hspace{1cm} (4)

where $T_L$ is the load torque. $T_i$ can be considered to comprise of:

$$T_L = J_{sc} \ddot{\omega}_{sc} + c_{sc} \dot{\omega}_{sc} + T_d$$  \hspace{1cm} (5)

Where, $J_{sc}$ and $c_{sc}$ are the steady-state inertia and damping constant of the loaded screw, $\dot{\omega}_{n}$ is the screw acceleration, and $T_d$ represents any additional disturbance torque such as a change in material, a change in fill level, increase in torque due to forcing un-melted particles through narrowing screw channel etc.

If no disturbance torque occurs there is no change in screw speed and both $T_L$ and $T_m$ are constants. However, as shown in Figure 1, if a disturbance occurs this will result in a transient acceleration or deceleration of the screw:

$$T_L - T_d = J_{sc} \ddot{\omega}_{sc} + c_{sc} \dot{\omega}_{sc}$$  \hspace{1cm} (6)

A transient decrease in screw speed causes an increase in armature current, and hence torque, for a standard,
armature-controlled d.c. motor (due to a reduction in back e.m.f., $E_b$). Hence the motor torque will increase to match the disturbance torque. A negative disturbance torque will obviously have the opposite effect. The motor is also fitted with a speed controller which aims to maintain the screw speed at its set value, for an armature speed controlled motor; this is achieved by adjusting the armature voltage [6].

Hence, it is clear that for an extruder with a d.c. motor, motor armature current or the product of motor armature current and field current tracks fluctuations in screw load torque induced by process disturbances (from equations (1) & (4)).

**Experimental setup & Procedures**

All measurements were carried out on a 63.5mm diameter single screw extruder (Davis Standard BC-60). A tapered compression screw with 3:1 compression ratio (Feed-4D, Compression-10D, Metering-10D) was used to process materials. The extruder was fitted with an adaptor prior to a short round die with a 12mm bore. The barrel has four separate temperature zones equipped with Davis Standard ‘Dual Therm’ controllers.

The extruder drive is a horizontal type SEDC (separately excited direct current) motor which has ratings: 460Vdc, 50.0 hp (30.5kW), at the speed 1600rpm. The motor and screw are connected through a fixed gearbox with a ratio of 13.6:1, hence gearbox efficiency is relatively constant at all speeds (~96%). Motor speed was controlled by a speed controller (MENTOR II) based on speed feedback obtained through a DC tachometer generator.

The extruder was instrumented with two high voltage probes to collect armature and field voltage data (Testoon GE8115) and two current probes were used to measure armature and field current (Fluke PR430 and PR1001). The melt pressure was recorded by a Dynisco TPT463E pressure transducer close to the screw tip. A LabVIEW software programme was developed to communicate between the experimental instruments and a PC. All signals were acquired at 10kHz using a 16-bit DAQ card (National Instruments PCMCIA 6036E) through a SC-2345 connector box. Amplification was applied to the armature current, field current, and melt pressure signals. A high sampling speed was necessary as the electrical signals contain high frequencies associated with rectification of the a.c. supply.

Experimental trials were carried out on a virgin HDPE, HM5411, from BP Chemicals (MFI – 0.12g/10min and density 0.952g/cm³) and recycled black HDPE (MFI – 0.16g/10min and density 0.967g/cm³). MFI values are presented according to the ISO 1133 standard (190°C, 2.16kg). From here onwards, recycled black HDPE, (RH), and virgin HDPE, (VH), are referred as recycled material and virgin material respectively. Extruder temperature settings were fixed as described in Table. 1

**Table. 1: Extruder barrel temperature settings**

<table>
<thead>
<tr>
<th>Zones</th>
<th>Clamp Ring</th>
<th>Adapter</th>
<th>Die</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>170</td>
<td>185</td>
</tr>
<tr>
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The screw speed was adjusted from 10rpm to 90rpm in step sizes of 20rpm, with the extruder running for about nine minutes at each speed. Mass throughput at each speed was measured by collecting and weighing the output over two minutes.

**Results and Discussion**

The measured average mass throughputs at each screw speed for both materials are shown below.

![Fig. 2: Mass throughput at each speed](image)

The graph shows linear mass throughput rates with increasing screw speed for the recycled material. The virgin material had very low mass throughput rates at the 10 and 30rpm screw speeds, and there was obviously some problem in conveying of polymer at these conditions. At higher speeds the throughput of virgin material was lower than that of the recycled material, probably due to higher viscosity of the virgin material (as indicated by the MFI).

Solid particles were clearly observed in the melt output during processing of the virgin material at 90rpm. There were no poorly melted particles visually observed in the recycled polymer output at any speed. The recycled material had a smaller pellet size (roughly three times smaller than that of the virgin material), previous work has shown that a smaller pellet size enhances heat conduction resulting in a shorter melting time [7,8]. Differing thermal properties may also affect the melting rate.

**Melt Pressure**

The measured melt pressure signals over the nine minutes at each screw speed are shown in Figure 3. It is clear that melt pressure is higher for the virgin material than the recycled material at 50, 70, & 90rpm.
even though mass throughput is lower. Again, this is expected due to higher viscosity.

Fig. 3: Melt pressure for recycled and virgin HDPE
However, at 10 and 30rpm the melt pressure for the virgin material is very low, correlating with the low mass throughput conditions shown in Figure 2. The mean melt pressure at each speed is shown in Figure 4.

Fig. 4: Mean melt pressure at each screw speed

As shown in Figure 5, the highest melt pressure variations were observed at 10rpm and 50rpm for the recycled material and virgin materials respectively. The higher melt pressure variance at 50rpm for virgin material may be due to an unsteady process condition soon after increasing the mass throughput rate which was previously very low.

Motor torque
The motor torque at each screw speed was estimated from measured d.c. signals. A three phase a.c. supply was connected to the motor which is converted to a d.c. current via full wave rectification. The appearance of the measured rectified armature current signals at different screw speeds is shown in Figure 6.

RMS (root mean square) values of the armature and field currents were calculated from the measured instantaneous signals. RMS values (calculated over each period where one period = 0.02s) were considered in estimation of the motor torque. The constant $K_t K_f$ (1) was assumed as equal to 1. That is because the main concern is to investigate the fluctuations of motor torque (variations of $I_f I_a$) rather than the absolute torque level. $K_t K_f$ is a constant for a particular motor and hence the level of the torque also can be compared.

Over the first minute

Over nine minutes

Fig. 6: Appearance of the measured current signals

Fig. 7: Motor torque variations for recycled (RH) & virgin (VH) HDPE.

Estimated torque signals over time are presented in Figure 7 for both the recycled and virgin materials. Clearly, motor torque increases as screw speed
increases. It can be seen that the motor torque signal contains similar fluctuations as observed in the melt pressure. Fig. 7-b, 90rpm signal (marked on the figure) shows a sharp step change of the torque level. This change is easily observable in the field current signal which responds to large, sustained changes in load due to motor speed controller action. Such a change is attributed to sudden process changes along the screw. The sudden change observed here, about 15s after increasing the speed from 70 to 90rpm, may be due to the fact that at 90rpm the virgin material did not completely melt, hence higher viscosity material begins to purge out the more molten material in front of it. This sudden step change is not observable in the corresponding pressure signal which showed a gradual increase following the speed change. Other sudden changes in torque were also observed occasionally in the recycled material but again were not detected by the pressure signal.

The mean motor torque and torque variance against screw speed are shown in Figures 8 and 9 respectively.

**Fig. 8: Mean motor torque at each screw speed**

For the recycled material, the rate of increase of motor torque reduces at higher screw speeds, which is expected due to a reduction in the polymer viscosity with shear-thinning, resulting in lower back-pressure than would otherwise occur. However, this is not observed for the virgin material, where both the pressure and torque signals increase linearly from 50 to 90rpm. This may be due to the fact that at higher screw speeds the material was not being completely melted and hence the viscosity remains high. The mean torque is always higher for the recycled material even at 90rpm where the throughput rate is similar but the pressure (and therefore viscosity) is higher for the virgin material. As the throughput rates are similar, the inertia in each case would be expected to be similar; therefore the friction must be higher for the recycled polymer. As the viscosity appears to be lower, it suggests that the solid friction component must be higher for the recycled material. This would also explain the more efficient conveying seen for this material. Menning [3] found that the torque in the solids conveying zone was much higher than the later zones, and the results here would also suggest that the solids region dominates the load torque signal.

**Fig. 9: Motor torque variance at each screw speed**

The variance of the motor torque signal reduces with screw speed for the recycled material. However, for the virgin material torque variance increases up to 50rpm and starts to decrease afterwards, this is similar to the pattern seen in melt pressure.

The average specific energy consumption (the energy consumed by the motor to produce 1g of extrudate) was calculated from the mean r.m.s values of the armature and field electrical variables at each screw speed. From Figure 10, it is clear that the virgin material consumed relatively high power per gram of extrudate at 10 and 30rpm where very low mass throughputs were achieved. Specific energy consumption decreases for both materials as speed increases above 50rpm with the most efficient operating point in terms of motor power consumption occurring at 90rpm.

**Fig. 10: Motor specific power consumption at each speed**

The effect of barrel temperature settings on motor specific power consumption was observed by repeating the experiment at slightly lower and higher temperature settings than shown in Table 1. Specific power consumption increased slightly at all screw speeds with a decrease in barrel temperature settings, and decreased at all screw speeds with higher temperature settings. This trend was the same for both materials and can be attributed to changes in polymer viscosity at the barrel wall.

**Frequency Analysis**

Frequency analysis of the motor torque and melt pressure signals was carried out to produce power
spectral density (PSD) spectra of the estimated torque signals for both materials at different screw speeds. The Welch method was applied in a Hamming window equal to the data length. This method tends to decrease the variance due to spectral leakage of the power spectral density (PSD) estimate relative to computing the power spectrum over the entire data.

Only data acquired during the first 3.5 mins at each screw speed were used in the frequency studies due to difficulties encountered in processing a greater number of data points. While frequencies up to 5kHz can be observed from the data, high frequency signals are most likely due to conditioning of the electrical signals and are not relevant to the process. For this reason only frequencies up to 50Hz are displayed in the spectra. The spectra for 10 to 50 rpm are shown in Figures 11-13, with the low frequency components displayed separately for clarity.

Power spectra related to the pressure signals for both materials at 10 and 50rpm speeds are shown in Figures 14 & 15. It can be observed that the low frequency and screw frequency content of both the pressure and torque signals is similar, but that frequencies above 10Hz cannot be seen in the pressure signals. The information provided by the pressure signals may be restricted by the location and the response time limitations of the pressure transducer. The dynamic response of strain-gauge type transducers such as used here is not as rapid as piezo-electric/resistive or optical transducers [9].
By comparing the frequency spectra in Figures 11-15, it can be seen that both torque and pressure spectra show several low frequency components (components below screw frequency) at all screw speeds. These low frequency components are slightly higher for the recycled material than the virgin material at 10rpm.

The presence of low frequency fluctuations has been attributed to break up of the solid polymer bed or poor temperature control by previous workers [9,10,11]. Poor temperature control is unlikely to be a factor in this study as all temperature controllers were well tuned. Solid bed break-up occurs when, rather than the solid bed gradually dissipating as melting proceeds, shearing forces acting on the bed cause it to break up. Wong and Zue et al. [12], state that for a given screw configuration, occurrence of solid bed break up is largely dependent on the screw speed and other processing conditions (e.g., temperature and pressure). According to their experimental and theoretical investigations, the screw length over which solid bed break-up occurs and the breaking frequency increases with increasing screw speed since a greater shearing effect is introduced. However, in this study the intensity of low frequency components of both torque and pressure did not increase with screw speed. The highest low frequency intensity occurred at 10rpm for the recycled material and 50rpm for the virgin material; the conditions with the highest total melt pressure and torque variations. This suggests that the low frequency components are not due to solid bed break-up, although this may be occurring at higher speeds. Also, material variation may be a factor for the recycled polymer.

Screw frequency fluctuations are significantly higher for the virgin material than the recycled material at all screw speeds except 10rpm. Screw frequency fluctuations may occur due to variations in the intake of polymer from the feed hopper into the feed zone [10] and by the pressure difference across the screw flight which is inherent to the conveying process [9]. Rauwendaal [9] argues that solids conveying instabilities can occur due to flow problems in the feed hopper; internal deformation of the solid bed in the screw channel; and insufficient friction against the barrel surface. Furthermore, he states that solids conveying conditions depend on pellet size, pellet shape, screw speed, and temperature of the feeding zone. The results here suggest that the virgin material was more prone to solid conveying issues; this may be due to the fact that it had larger and smoother pellets than that of the recycled polymer. Also the polymer coefficient of friction is sensitive to temperature and pressure and changing operating conditions can have a significant effect. This may explain why fluctuations were worst for the recycled material at 10rpm and the virgin material at 50rpm. Derezinski [1] noted that torque fluctuations were very sensitive to the barrel temperature in the feed zone suggesting that solids conveying issues may dominate the torque signal. The results here would seem to support this, and would explain why low frequency fluctuations did not...
increase as expected when incomplete melting was observed at high speeds.

The high frequency components (above screw rotation frequency), of torque fluctuations are much larger in magnitude than lower frequency fluctuations for both materials. The high frequency content of the pressure spectra is always greater for the virgin material than the recycled material. The virgin material shows greater magnitude of fluctuations above screw frequency up to a certain point, at frequencies above this point the recycled material displays higher magnitudes. The frequency at which this occurs is different at different screw speeds. At 10, 70, and 90rpm this occurs around 8Hz. At 30rpm and 50rpm this transition occurs at 30Hz and 20Hz respectively. It should be noted that torque fluctuations occur at roughly the same frequencies for both materials at all speeds suggesting these may be due to the machine rather than material properties. Pressure fluctuations also occur at the same frequencies, however, these are not as significant as in the torque spectra and the pressure spectra do not carry high frequency components above 10Hz.

Possible causes of these high frequency components may include machine vibrations, and transient components introduced in the torque signal due to inertia and damping and the speed controller action (right hand side terms of equation (6)). Such transients will depend on the frequency and magnitude of the disturbance torque fluctuations. It is interesting that the virgin material which is shown to be more prone to melting and conveying problems contains higher magnitudes of torque fluctuations in a certain frequency range, while the recycled material with variable feed properties contains higher magnitudes of torque fluctuations in a different frequency range. Further analysis is ongoing to gain better understanding of these effects.

Conclusions

Analysis of motor torque and mass throughput data showed that motor specific energy consumption was lower at higher screw speeds and depends on the barrel temperature settings. However, selection of suitable screw speed and barrel temperature settings depends on the required melt quality.

Concurrent analysis of pressure and torque signals, together with visual inspection of the output, suggests that the virgin polymer suffered solids conveying problems at lower screw speeds and melting problems at higher screw speeds. A high torque level observed for the recycled polymer is likely due to a higher solid friction component, which may explain the more efficient conveying observed at low screw speeds. The virgin polymer resulted in higher pressures at speeds of 50rpm and above, where it increased linearly. The lack of a shear-thinning curve is a possible indicator that viscosity remained high due to poor melting at higher speeds. The pressure signal is sensitive to melt throughput and viscosity at the die, while the torque signal appears to be much more sensitive to conditions in the solids conveying zone of the extruder.

Frequency analysis showed that in general, pressure and torque signals display a similar pattern of fluctuations up to and including screw frequency. However, additional dynamics could be observed in the torque signals which were not detected by the pressure measurement at the end of the barrel. Large step changes of load could be observed in the torque signal under certain processing conditions, this indicated a sudden change in the process which could not be detected in the pressure signal close to the screw tip. In the case of the separately excited field motor used in this work, these dynamics could be observed very easily by simply tracking the field current signal. Also, observation of the torque signal shows potential to utilize high frequency information for the analysis of processing issues.

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