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ULTRASONIC DIAGNOSIS OF THE VIBRATION BEHAVIOR OF SCREWS IN A SINGLE SCREW EXTRUDER

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Abstract

Ultrasonic diagnostic method of screw behavior during extrusion has been designed, developed, and evaluated for a single screw extruder. It was found that under the same processing conditions and depending on the past history of the equipment usage, the vibration behavior of screws in the inspected processing equipment could vary noticeably and the vibration pattern repeated itself at every two screw revolutions. Results suggest that the vibration behavior of the screw is dictated by how the screw is engaged in and the status of the gearbox.

Introduction

Screw design is one of the most important elements in any polymer extrusion process development and has been the focus of extensive theoretical, experimental, and simulation studies [1]. However, the dynamic mechanical behavior of the screw shaft itself during extrusion does not draw much attention, although it is widely accepted that a misaligned screw abrading on the barrel could be harmful to the product quality; hence have serious financial consequences. It is not uncommon to see that the quality of production varies from time to time. Most often the manufacturer tends to put blame on resin quality and inconsistency. While on many occasions this is true, there are other cases where inconsistent behavior of the processing equipment is responsible. The goal of this paper is to present an ultrasonic technology for the diagnosis of a screw shaft behavior and some tests results under a range of processing conditions. The study has shown that under the same processing conditions a screw can indeed behave inconsistently and thus could be blamed for inconsistent product quality.

Description of the test method

Four ultrasound transducers (UT) are mounted in the terminal zone of the barrel of a single screw extruder (Figure 1) in 90º intervals, orthogonally to the screw surface (Figure 2). Each UT continuously sends 5-MHz diagnostic ultrasonic pulses to the screw surface at a rate ranging from 600 to 700 pulses per screw revolution and keeps capturing the echoes reflected by the rotating screw. Every pulse wave is reflected back and forth several times between the UT and screw before dying out. The time delay between two consecutive echoes is the round-trip time of flight (TOF) of ultrasound signal from the UT to the screw. By measuring this time τ and by knowing the sound speed V in the polymer, the gap between the UT and the screw can be determined. Although a diagnostic ultrasonic wave can be reflected by different areas of the screw when it is rotating, echoes reflected from the tip of screw flight are of interest. As shown in Figure 3, the position and length of the signal acquisition window are adjusted in such a way that only the first two echoes reflected from screw flight tip are recorded. For a single flight screw, each UT will only see once the flight passing by during one screw revolution. If the screw has double flights in the probed section, flight echoes will appear twice in the signal acquisition window during each screw revolution. The four UT's are synchronized in such a way that the movement of the screw is inspected simultaneously by them all. The melt pressure, P, and temperature, T, in the die zone are measured at the same time. The P, T, and ultrasound signals are acquired with a PC-based high speed ultrasound system, custom-designed and built in the laboratory [2, 3].

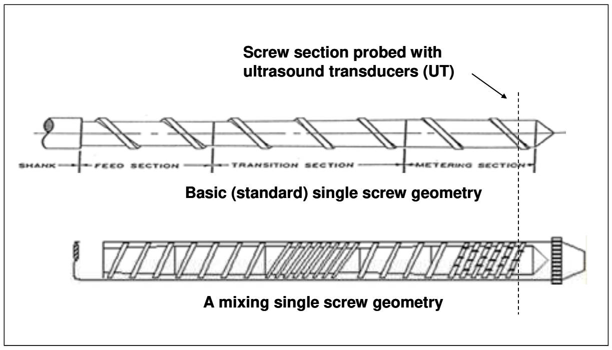

Figure 1. Configuration of two screws used in this work: (top) #1 the basic single flight conveying screw, and (bottom) #2 the mixing screw. The dashed line indicates the ultrasonically probed section.

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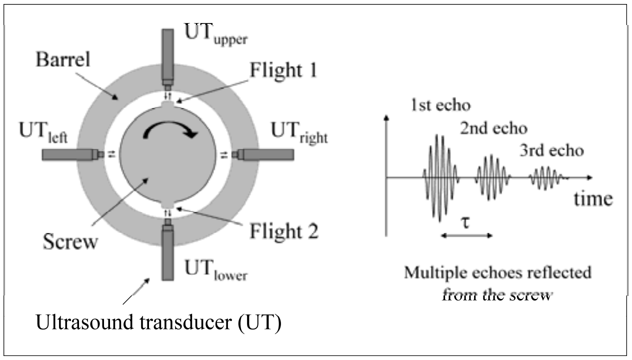

Figure 2. Four ultrasound transducers (UT) are flush-mounted in the terminal zone of the extruder barrel, perpendicularly to its surface. Each UT sends ultrasonic pulses and captures the echoes reflected from the screw. The time delay between two consecutive echoes (right) is the round-trip travel time between the UT and the screw.

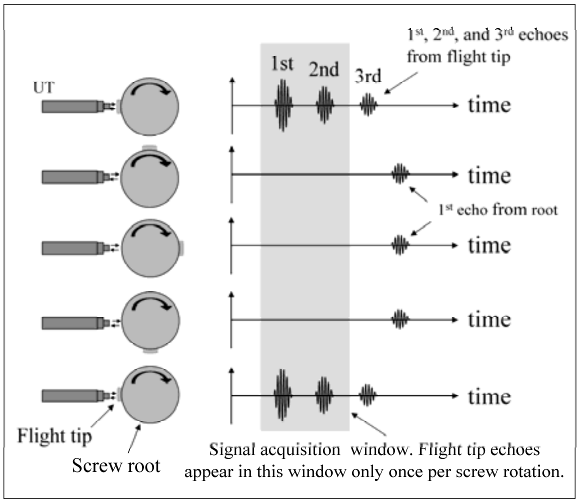

Figure 3. Echo signals reflected from the screw flight tip (left) appear in the signal acquisition window once per single screw rotation (right).

Results and discussions

Two types of screws shown in Figure 1 were tested: a basic single flight conveying screw (#1) [1]; and a mixing screw with a double flight mixing element in the terminal zone (#2). Four ultrasound transducers (UT) were mounted in the terminal zone of the barrel of a 63.5 mm FLAG single screw extruder as illustrated in Figure 2. An injection molding grade polypropylene (ProFax PDC1274 from Basell Polyolefins) with a melt flow rate MFR = 12 g/10 min was chosen for the tests. Owing to its relatively high MFR the screw vibrations were expected to be more severe (the vibrations could be damped by more viscous and elastic polymer).

Figure 4 shows an echo graphic image of screw #1 acquired at the upper UT location during a test in which the screw speed was 20 RPM. In the Figure, a total of 12,250 ultrasonic echo signals are displayed from left to right on the horizontal axis (denoted as Acquisition number). The vertical axis in the Figure represents the sequence of sample points constituting each digitized signal. The vertical strips are the intensities or amplitudes of the 1st and 2nd ultrasonic echoes reflected from the screw flight tip when it passes in front of the UT. In the Figure two lines labeled as "Arrival lines" indicate respectively the earliest and the latest arrival positions of the 1st echo recorded during the screw rotation. The count of the flight tip echoes indicates recording for 17 screw revolutions. In this case, the screw vibrates steadily and the screw oscillation pattern repeated itself at every second revolution. Similar screw behavior was also observed at other three UT locations. It is noteworthy that this two-cycle repetition pattern of screw vibration has been observed with screw #2 in the same extruder as well. Furthermore, the two-cycle repetition phenomenon did not seem to be peculiar to this very extruder as we observed the same phenomenon on a production extruder inspected recently.

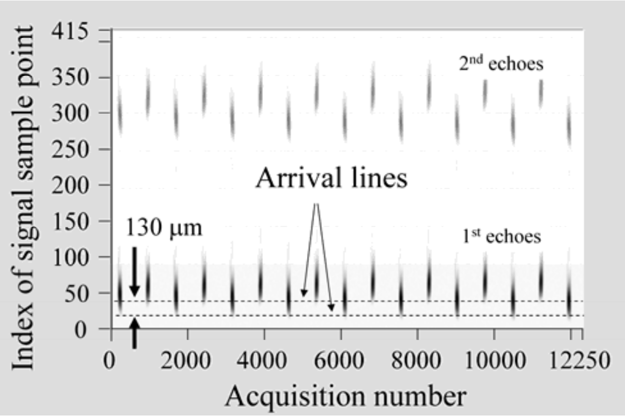

Figure 4. Echo signals reflected by screw #1 at 20 RPM and received by the upper UT. The melt pressure and temperature were about 27 MPa (3930 psi) and 200 ºC, respectively. The screw-barrel gap is steady 130 μm.

In a series of tests, the extrusion started at 100 RPM. Then the screw speed was reduced sequentially to 50, 20, and 5 RPM. Table 1 lists screw deviations measured at the four screw speeds after the screw vibration stabilized and at the left and right UT's locations. The significant difference in the oscillation magnitude at the two locations indicates that the screw movement was asymmetrical. For this particular test series, the screw behavior at 50 and 20 RPM were quite similar despite the reduced screw speed and P. The oscillation at 5 RPM was well balanced (about the same at the two UT locations), more so than at higher screw speeds. It is inferred that more consistent product quality might be expected at this screw speed, but further study relating melt quality to screw behavior is needed to validate this conjecture. The results imply that, at least for this test series, a decrease in screw oscillation amplitude at the left UT location was accompanied by an increase in screw oscillation amplitude at the right UT location. It is to note that at different screw speeds listed in Table 1 the sum of gap deviations measured at the left and right UTs locations was not constant. This is because the gaps at the left and right UTs locations were not measured at the same moment as the probed screw had only one flight that was not seen simultaneously by both of the UTs.

Table 1. Test results at four screw speeds (in sequential order)

Screw speed (RPM)	**Melt pressure (MPa)**	**$\mathit{\Delta}$ at left UT (μm)**	**$\mathit{\Delta}$ at right UT (μm)**
100	39.3	209	30
50	32.8	161	129
20	25.5	169	126
5	15.5	139	138

Experimental results indicate that at the same screw speed, T and P, the screw behavior is not necessarily the same, as the past screw speed and P affect it as well. For example, in another test series, the extrusion started at 5 RPM with the die exit fully open. Then the die gap was reduced and the screw speed increased to 20, 50 and 100 RPM. After that, the screw speed was reduced back to 5 RPM. The variation of the radial gap, denoted as $\mathit{\Delta}$, measured at the left UT location versus the common logarithm of pressure (P) is displayed in Figure 5 with the linear regression line for tests # 1 to 5. For the 1st five tests, $\mathit{\Delta}$ linearly increases with *log*(P), suggesting a gradual engagement of the screw into the gearbox sleeve at increasing die backpressure. Consequently, the test #6 shows a different behavior – the screw oscillation is noticeably larger than what might be expected for 5 RPM and P = 8.1 MPa. The reason could well be that once the screw is pushed into the gearbox sleeve, it does not return to its initial axial position when the die backpressure is reduced. Thus, it seems that the origin of screw vibration is related to some misalignment of the sleeve or the gearbox itself.

In principle, owing to the viscoelastic character of molten polymer, freely rotating crew should be hydrodynamically balanced – any deviation from the axial position would generate pressure forcing it back. The screw oscillation observed only after high axial pressure on the die forces it deep into the gearbox implies that it is the screw mounting sleeve that forces screw misalignment. This conjecture is further supported by data listed in Table 2 for tests at 5 RPM under different processing conditions (e.g., different die gap, tests in different days, at the start of a test series or after some tests at higher screw speed). Here, the data do not suggest any correlation between $\mathit{\Delta}$ and P.

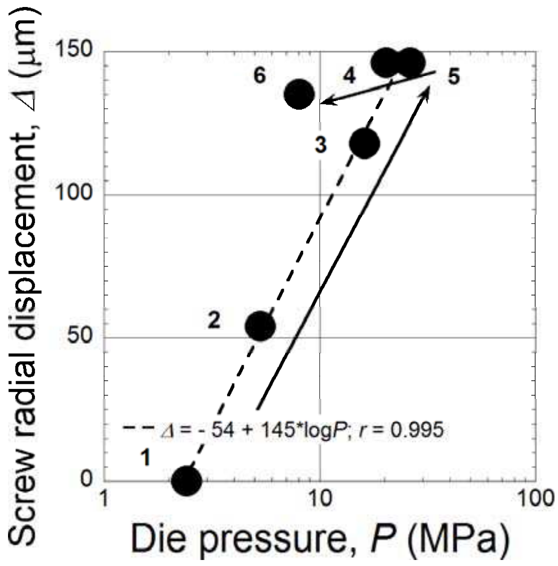

Figure 5. The screw #1 deviation $\mathit{\Delta}$ is plotted vs. common logarithm of P. The deviation was measured at the left UT location. The numerals and arrows in the Figure indicate the sequence of the tests. The linear regression (dashed line) was made for tests #1 – 5.

Table 2. Results of tests carried out at 5 RPM (in historical sequence)*

Melt pressure (MPa)	**$\mathit{\Delta}$ at left UT (μm)**
2.4	0
8.1	130
17.8	160
15.5	139
16.6	0
16.3	19
16.5	0
7.6	0

*: 0 represents cases where screw deviation was not noticeable.

Conclusions

An ultrasonic screw diagnostic technology that involves simultaneous use of 4 ultrasound transducers at the metering zone of a single screw extruder has been presented. The technology leads to valuable insight on how a screw shaft may behave under various processing conditions. The results suggest that the origin of screw vibration is the misalignment of the screw mounting in the gearbox sleeve. Depending on how the screw is engaged into the gearbox sleeve, the amplitude of the screw oscillation will vary, thus its behavior seems inconsistent.

Once the screw is fully engaged in the gearbox, its vibration behavior becomes insensitive to melt pressure and screw speed.

Acknowledgements

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Key Words: Ultrasound, Screw vibration, Extruder