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FEASIBILITY STUDEY OF BLOCKAGE DETECTION INSIDE PIPES USING GUIDED ULTRASONIC WAVES

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Abstract

It has been reported that in principle sludge and blockages in pipes can be detected and characterized by using ultrasonic guided waves. The model idealised the sludge to be an asymmetrically uniform layer that is well bonded to the internal surface of the pipe wall. However, in practice, sludge layers normally have a very irregular shape, an asymmetrical circumferential profile and also uncertain bonding state. These practical issues complicate the testing and perhaps bring some different new features to the guided wave modes. We investigated the different effects of these issues on the characteristics of guided wave. A general assessment of the potential of using guided ultrasonic waves to detect and characterize sludge blockage in practice is given.

Keywords: Guided ultrasonic waves, blockage detection, bi-layered pipe

1. Introduction

Guided ultrasonic waves have already been exploited for long range inspection of pipelines. It would be useful and attractive if they could be used also for detecting and characterizing sludge inside the pipe, since their capability of remote detection. An initial study was presented[1] , based on an idealised regular model which assumed the sludge to be an asymmetrically uniform layer that is well bonded to the internal surface of the pipe wall. However, in practice, blockage layers normally have a very irregular shape and complex adhesion properties. These practical issues complicate the testing and perhaps bring some different new features to the guided wave modes. In this paper, we proceed the work to investigate the different effects of each of practical issues on the two guided wave measurement approaches developed before. Finally we give a general assessment of the potential of using guided ultrasonic waves to detect and characterize sludge and blockage in practice.

2. Previous Work

An idealised model of an aluminum pipe (16 mm ID, 1.4mm wall thickness) with a sludge layer (6mm thickness epoxy), namely the ‘ bilayered pipe’, was used in the previous study (shown in Fig.1) [1]. The fundamental torsional mode T(0,1) was chosen for the study. The change brought by the sludge layer on the propagation of the torsional waves can be predicted by comparing the group velocity dispersions of the torsional modes in the free and the bilayer pipes (shown in Fig. 2) calculated by a modeling software DISPERSE[2]. Figure 2 shows that in the same frequency range there are more torsional modes occurring in the bilayered pipe compared to the single T(0,1) mode in the free pipe. With the occurrence of the new modes, new cutoff frequencies are generated accordingly which are determined by the thickness and the shear bulk velocity of the sludge layer. Also, the modes of the bilayered pipe are very dispersive, unlike the T(0,1) mode of the free pipe which always keeps a constant velocity value for all frequencies.

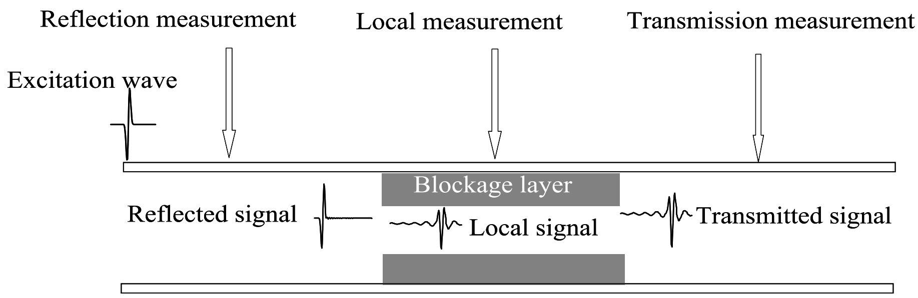

Figure 1. Schematic of the idealised model of a pipe with a sludge layer.

We developed two measurement ideas to detect and even characterize the layer inside the pipe. The model consists of a pipe locally coated with an epoxy layer inside (Fig. 1). The T(0,1) mode is excited in the free pipe region; when it reaches the bilayered pipe region starts, due to the acoustic impedance change, part of the T(0,1) mode will be reflected back to the free pipe, while part will be transmitted into the bilayered pipe region and propagate further.

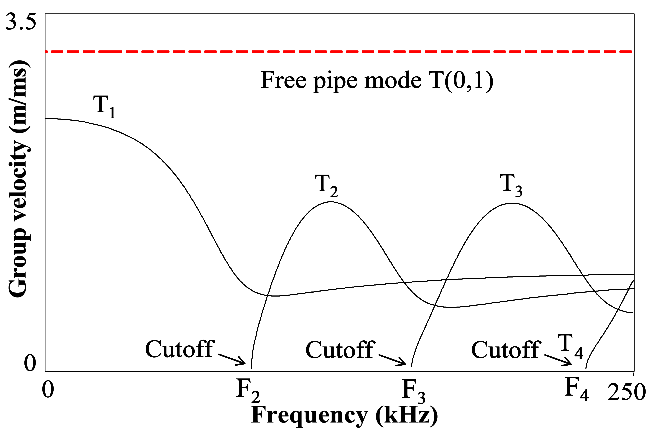

Figure 2. Group velocity dispersion curves of torsional modes in the free (red line) and the bilayered (black curves) pipe (simulated by DISPERSE1).

The first measurement is carried out on the free pipe region, measuring the reflection of the T(0,1) mode from the entry point of the layer inside the pipe (Fig.1). The arrival time of the reflection can be used to locate the sludge. The reflection coefficient spectrum (ratio of the amplitude spectrum of the reflected signal to that of the incident signal) was calculated to choose the frequencies to obtain the strongest reflections. It was found that the peaks of the magnitude of the reflection coefficient pectrum occur just at the cutoff frequencies of the torsional modes in the bilayered pipe (Fig. 3a). When the cutoff frequencies have been measured from the refection coefficient spectrum, the thickness of the sludge layer can be quantified, provided that the bulk shear velocity has been known beforehand.

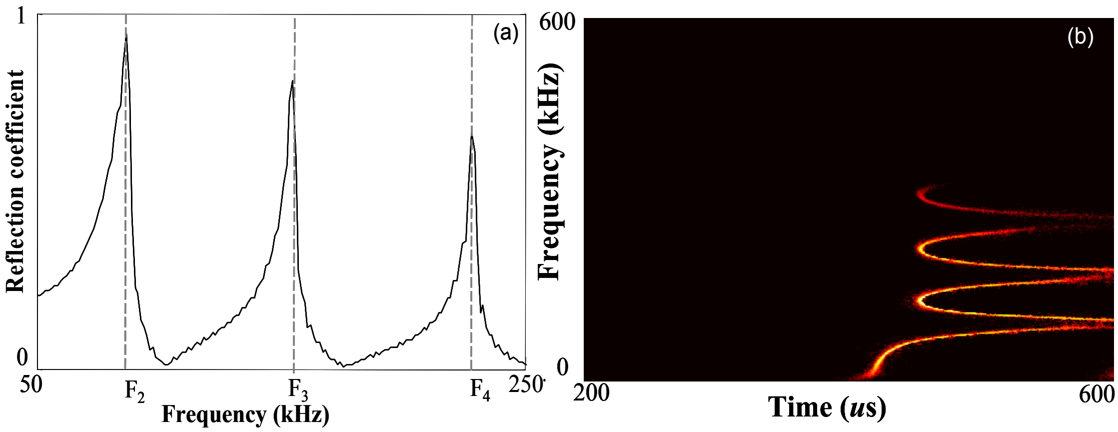

Figure 3 (a). Reflection coefficient spectrum of the bilayereed pipe. (b). Reassigned spectrogram analysis of the local signal in the bilayered pipe.

The second measurement is performed at a local position of the bilayered pipe region, where some energy of excitation signal (wide band pulse excitation) of the free pipe mode T(0,1) has been converted into the bilayered pipe modes (Fig.1). Only one measured time-domain signal is needed. Then, a time-frequency signal processing tool, reassigned spectrogram[3] was used to analysis the local signal (Fig. 3b). It reveals for each mode, the arrival time of each frequency contained in the local signal which is determined by the group velocity. The revealed dispersion nature of the local signal can be a clear indicator of the sludge since the signal in the clean pipe is non dispersive. The extraction of the thickness of the sludge can be achieved by best fitting modelled dispersion curves to the measured ones provided the shear bulk velocity of the sludge and the length of the layer was known. The local measurement can be easily extended to another remote measurement, the transmission measurement, which is to measure the transmission signal after the blocked pipe region (shown in Fig.1). Thanks to the non-dispersive nature of the signal propagating in the clean pipe region, the principle of the local measurement is fully applicable to the transmission measurement. Following study will mainly discuss on the transmission measurement.

3. Practical Issues Considerations: Simulations

3.1 Imperfect Bonding State

The effect of the bonding state is first simulated by the finite element (FE) simulation by using the spring layer model which has been commonly used to simulate the imperfect bonding condition[4]. A thin fictitious layer (0.1 mm) is modelled between the pipe and the sludge layer to simulate a material that represents a shear spring with stiffness in the circumferential direction. The decreasing of bonding is simulated by reducing the shear stiffness of the spring layer. The effect of the imperfect bonding states on the dispersion curves of the torsional modes in the bilayered pipe is shown in Fig. 4. Four different values of the stiffness are chosen and for comparison the case of perfect boning is also given. For clarity, only the first two bilayered pipe modes are shown for each case. It shows that with the deceasing the bonding state the fist cutoff region occurs at lower frequencies. This gives rise to the corresponding influence on the reflection measurement. The peaks of the amplitude reflection coefficient spectrum shift to lower frequencies, which is shown in Fig 5a. This implies that in practice, the uncertain bonding state requires the detection to employ broadband frequency excitation to guarantee obtaining strong reflections from the sludge.

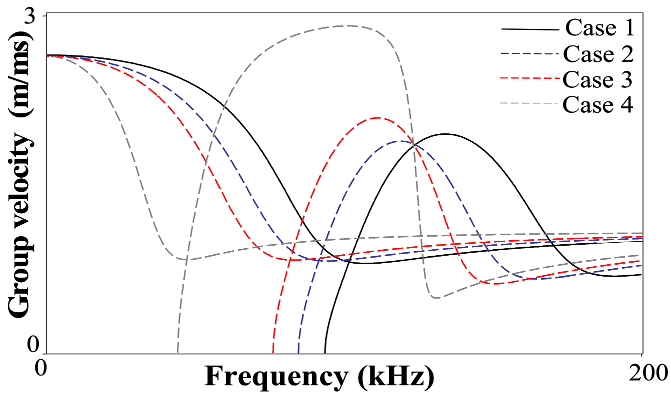

Figure 4. Dispersion curves of the torsional modes in the bilayered pipe with different bonding states. (**case 1**: $K_T \in \infty$, **case 2**: $K_T = 3.5\times10^{18} N/m^3$ **case 3**: $K_T = 1.75\times10^{18} N/m^3$, **case 4**: $K_T = 3.5\times10^{17} N/m^3$).

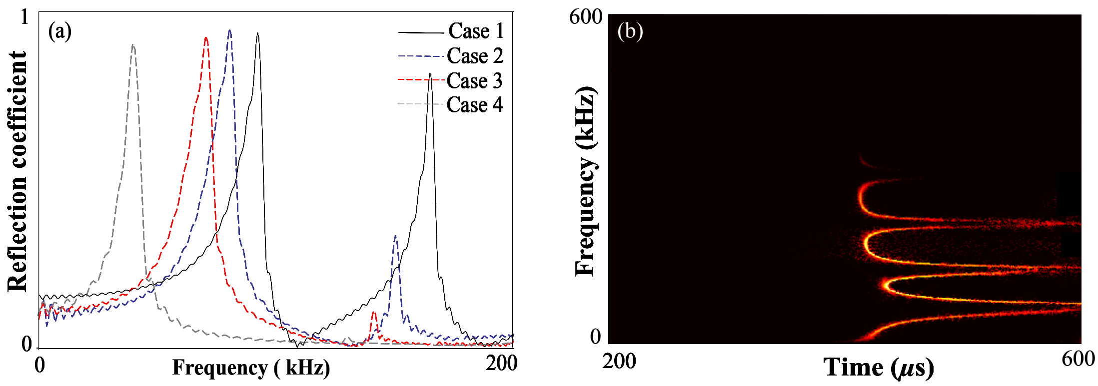

Figure 5 (a). Reflection coefficient spectrum obtained from the pipe with imperfectly bonded blockage layers. (b). Reassigned Spectrogram analysis of the transmitted signal in the pipe with imperfectly bonded blockage layer (case 2).

The reassigned spectrogram analysis of the simulated transmission signal is shown in Fig for case 2 ($K_T \in \infty$). It shows that the dispersion change of the transmitted signal still can be revealed in the case of the pipe with an imperfectly bonded blockage. The dispersion change also depends on the bonding state, this will not influence the detecting of the sludge thanks to the non-dispersive nature of the T(0,1) mode in the clean pipe; however, quantification the thickness of sludge layer becomes difficult due to the uncertainty of the bonding state in practice.

3.2 Tapered Interface + Varying Bonding State

It is very likely in practice that the sludge has inconsistent properties along its length, including thickness and bonding properties. We model a case that the sludge layer has tapered interface at both ends and varying bonding conditions at different stages (shown in Fig. 6). The stiffness of the spring layer in the middle is 10 times larger than that at both ends. This assumption is made to study the effect of abrupt bonding change along the sludge layer. The time trace of the reflection measurement (Fig 7a) shows the incident wave on its way to the blocked pipe region, and little reflection occurs from the entry point of the tapered sludge. Considerable reflection occurs later where there is abrupt bonding change, although the change of thickness at this point is very gentle. This implies that any abrupt change in bonding state will result in strong reflections regardless of the tapered interfaces. However, if the change of geometry and bonding state are gradual, then the reflections are weak. Essentially, bonding state, thickness and even material properties of the sludge all will influence the mode shape of the torsional mode, which is the source of the reflection. The more abrupt these change are, the stronger the relations will occur.

The reassigned spectrogram analysis of the transmission signal in this case is shown in Fig 7b. Dispersion change of the transmitted signal still can be revealed although there is some disturbance which is due to the varying bonding state and thickness of the sludge layer along its length.

4. Practical Issues Considerations: Experiments

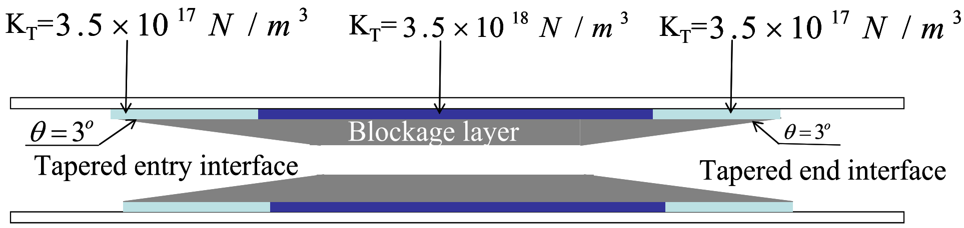

Figure 6. Schematic of the pipe with the sludge that has varying thickness and bonding state

Experiments have been carried out to validate the FE simulations. The experimental setup is shown in Fig. 8 More description can be found in Ref.1. Measurements are made at two positions of the pipe to measure the reflection and transmission signals respectively.

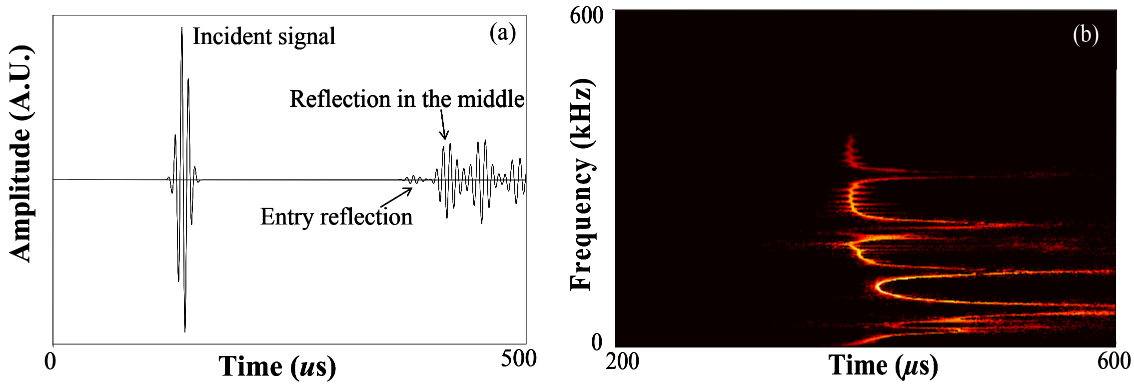

Figure 7 (a). Time trace of the incident signal and the reflected signals in the pipe with blockage layer of varying thickness and bonding state. (b). Reassigned Spectrogram analysis of the transmitted signal in the pipe with blockage layer of varying thickness and bonding state.

4.1 Model Case

An aluminum pipe with a press-fit axisymmetric epoxy layer (6mm uniform thickness) was made to represent the imperfect bonding case. The reflection measurement is measured at point 1 (shown in Fig. 8) and the amplitude reflection coefficient spectrum is shown in Fig 9. For comparison, the result of the good bonding case using a cast epoxy layer was also given [1]. The FE predictions for both cases are plotted in the same figure. The measured peaks of the reflection coefficient spectrum locate very well with the predicted ones. The agreement for the imperfect bonding case is by chance, since the stiffness is uncertain to us. However, both the measurements and simulation confirm that the imperfect bonding of the blockage shifts the peaks of the reflection coefficient spectrum to lower frequencies.

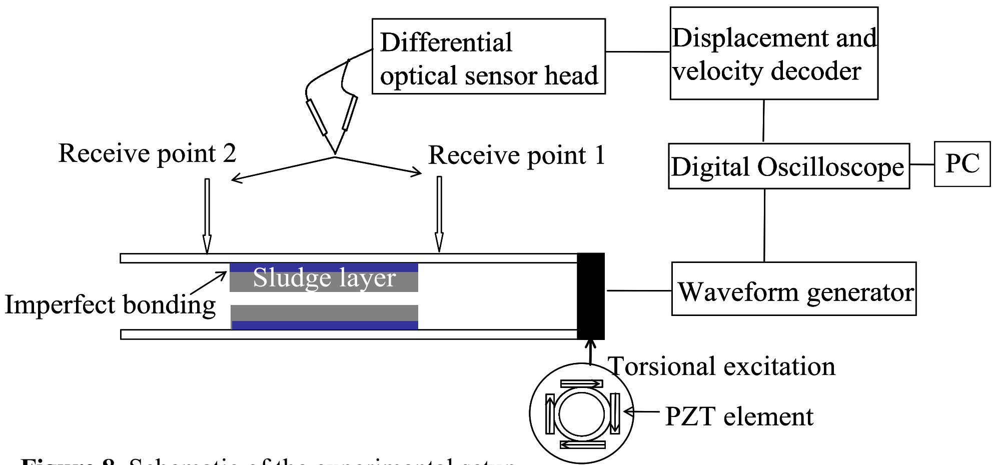

Figure 8. Schematic of the experimental setup

The transmission signal is measured at position 2. The reassigned spectrogram analysis of the transmission signal is shown in Fig 10b. For comparison, the reassigned spectrogram analysis of the excitation signal propagating in the clean pipe region (measured at position 1) is also given in Fig 10a. The presence of the sludge inside pipe clearly causes the transmission signal to be dispersive, while it is perfectly non-dispersive in the clean pipe. The first two cutoff regions can be identified as the frequencies being delayed due to the low propagating velocity of the torsional modes at their cutoff regions.

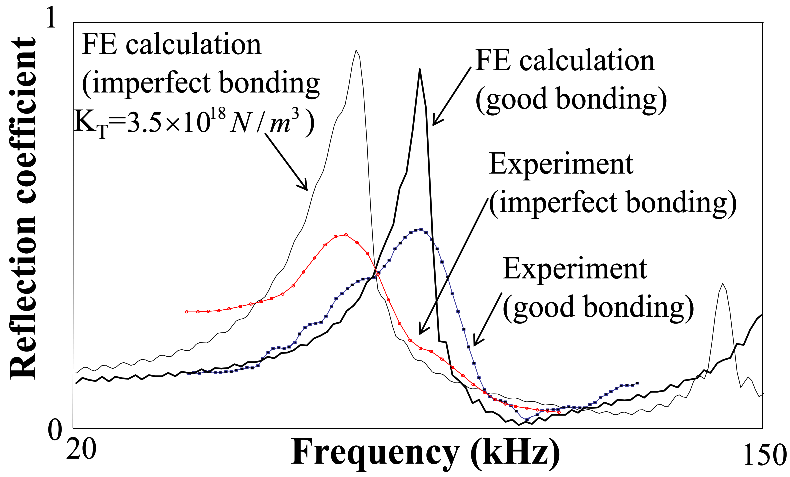

Figure 9. Reflection coefficient measured at point 1 from the samples with good bonding and imperfect bonding.

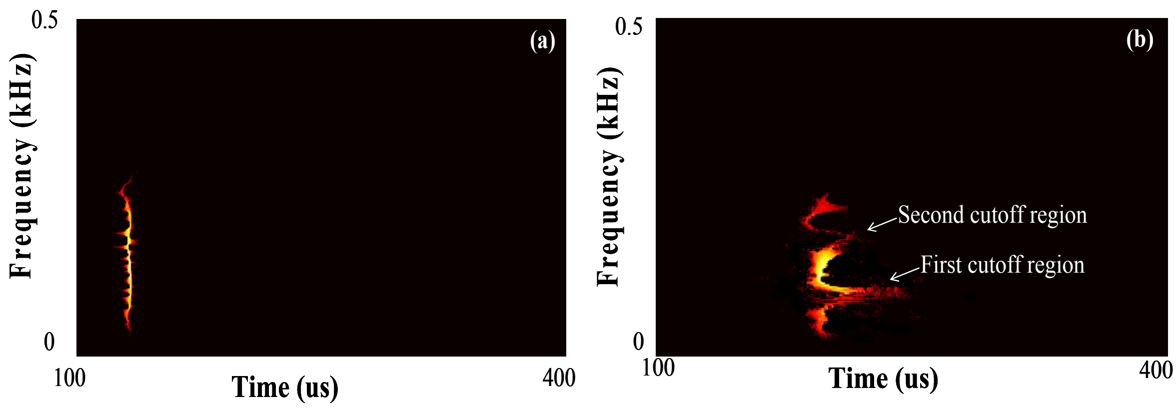

Figure 10. (a) Reassigned Spectrogram of the incident signal before the blocked pipe region (measured at point 1). (b) Reassigned Spectrogram of the transmitted signal after the blocked pipe region (measured at point 2).

4.2 Initial Study on Simulants of Real Blockage

Experiment is further performed on an aluminum pipe with random shaped blockage layer made by simulants of real blockage material. The time trace of the reflection measurement (Fig. 11) shows the incident signal followed by a little signal (reflection 1) which is the reflection from the entry point of the sludge. A much stronger signal arriving later is reflected from the middle of the blocked pipe (reflection 2). It is very likely that this strong reflection is due to the abrupt change of the bonding states, since there is no drastic thickness change of the sludge layer. This confirms that reflection may occur at different positions of the blocked pipe region, according to bonding conditions.

Transmission was not measured at point 2 due to its high attenuation caused by the damping of the blockage material. However, this may also be an indicator of the blockage, since the guide waves propagating in the clean metal pipe have little attenuation over long distance.

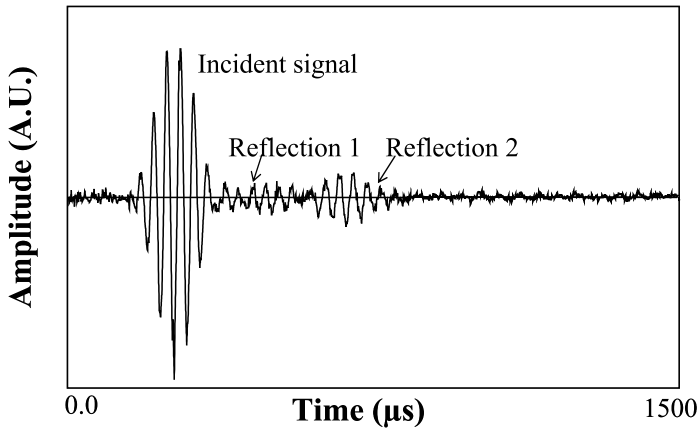

Figure 11. Time trace of the incident signal and the reflected signals measured at point 1.

5. Conclusions

This paper has further investigated the potential of sludge and blockage detection and characterization using guided torsional waves on the base of the idealized model. After considering the practical issues on the two guided wave measurements through FE simulations and experiment validations, an overall assessment can be summarized as follows.

A reflection can be caused by any abrupt change of blockage properties e.g. bonding state, thickness or material properties. The reflection measurement approach can locate the blockage. Transmission measurements can reveal the dispersion change caused by the blockage; however, the transmission measurement cannot locate the blockage. The large attenuation of the transmission caused by the blockage material damping may also be an indicator of the blockage. For reliable blockage detection, both the reflection and transmission measurements need to be used. Quantification of the extent of the blockage will be difficult.

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