EDDY CURRENT MEASUREMENT OF REMOTE TUBE POSITIONS IN CANDU REACTORS

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Abstract: Regular NDE inspections of CANDU® reactors are made by inserting probes into one of 380 pressure tubes that traverse the core. Each pressure tube is surrounded by a gas annulus and contained in a calandria tube. Separation between the pressure tube and calandria tubes is maintained by four spacers. Moderator water surrounds the calandria tubes. Auxiliary tubular assemblies within the moderator run perpendicular to the pressure tube for the injection of neutron poison and for mounting flux detectors. Laboratory tests have demonstrated the use of remote field eddy currents to measure the distance between the pressure tube and auxiliary tubes.

Implementation uses coils from two appropriately separated probes in existing inspection heads. These coils are the transmit coil used for sensing the spacers and the receive coil from a probe used to measure the gap between the pressure tube and its surrounding calandria tube. The axis of the transmit coil is aligned with the axis of the pressure tube. The receive coil axis is perpendicular to the transmit coil, and located near the inner diameter of the pressure tube. Although the coil spacing and orientation are not ideal, laboratory tests have demonstrated repeatable measurements under conditions of varying liftoff, pressure tube wall thickness and diameter, and gap between pressure tube and calandria tube. The experimental conditions, test cases, and results are presented.

Introduction: The basic configuration of the CANDU® reactor is shown in Figure 1. NDE inspection probes of the Atomic Energy of Canada Ltd. (AECL) Fuel Channel Inspection System (AFCIS) are delivered to the inside of the fuel channel Pressure Tubes (PTs) [1]. The PTs are mounted inside surrounding Calandria Tubes (CTs) that are within the moderator water. A gas annulus (gap) is maintained between the PT and CT by four "garter spring" spacers. AECL's various fuel channel inspection tools incorporate eddy current, ultrasonic, linear variable differential transformer, and optical technologies. Together, these sensors have demonstrated the ability to measure PT flaws, PT wall thickness, PT diameter, PT/CT gap, PT sag profile, and garter spring spacer position. However, these sensors do not measure the position of auxiliary assemblies such as liquid injection shutdown system (LISS) nozzles or other reactor components within the moderator. Attempts to measure LISS nozzle positions have been made using ultrasonic probes from within an unused Horizontal Flux Detector tube. Optical inspection using cameras positioned into the moderator from the top of the reactor has also been performed. The coverage and accuracy of these methods have not been fully satisfactory. Consequently, of the many inspection tasks for which the Remote Field Eddy Current (RFEC) technique could be applied, the present interest lies in measuring the CT to LISS nozzle distance. The other eddy current applications have already been addressed using conventional techniques [1,2,3].

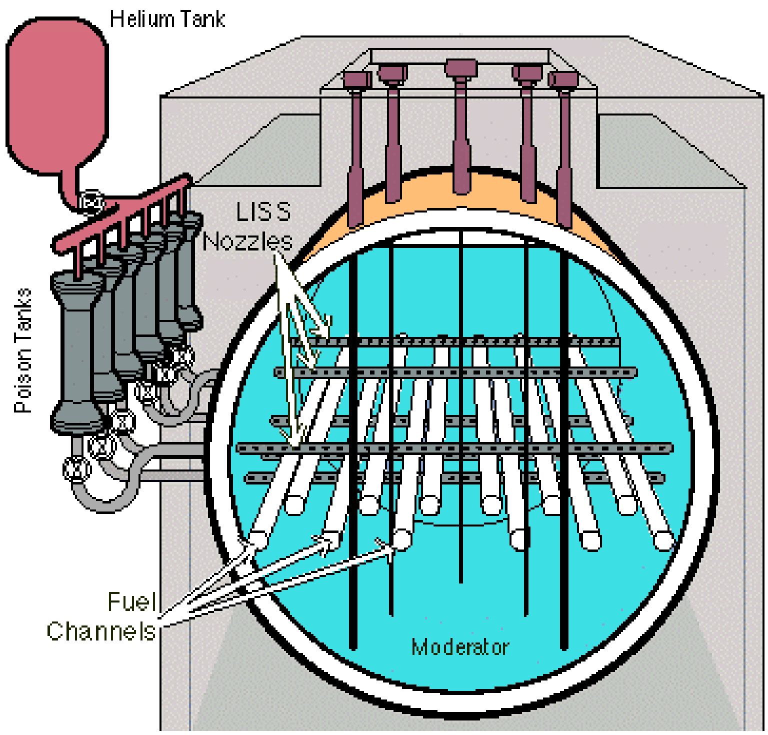

Figure 1: Basic CANDU® Configuration (Only 12 of 380 Fuel Channels Shown)

During fuel channel inspections, eddy current coils are delivered to the inside of the PT. The thick wall of the PT shields the probes from inspecting the surrounding CT and from inspecting other reactor structures such as LISS nozzles. In the RFEC method as applied to fuel channels, the transmit and receive coils are separated by sufficient distance that coupling of the coils is achieved predominately by magnetic flux lines that pass through the shielding tube(s); hence, perturbations in the coupling between the coils are predominately due to the material outside of the shielding tube(s).

The application of the RFEC technique has previously been investigated by AECL for use in measuring the clearance between the LISS nozzles and the CT. Others have investigated the use of RFEC in CANDU fuel channel geometries [4] and related concentric-tube geometries [5]. The RFEC effect has been shown to be enhanced by the use of shields to block direct coupling of the coils [6]. This latter work is applicable to the AECL garter spring spacer probe that employs field focusing elements [2].

The previous AECL examination of the RFEC method explored numerous coil orientations. Here we limited ourselves to the use of coils presently in use on the AFCIS. Specifically, the large diameter transmit bobbin coil in garter spring detection probes was used as the transmit coil. The radially oriented ≈15 mm diameter receive coil in the widely spaced PT/CT gap probe was used as the receive coil. Despite the comparatively reduced response, by restricting ourselves to the use of existing probe coils, the RFEC probe can be implemented with only minor changes to existing inspection systems.

Results are presented from laboratory tests of the RFEC technique used to measure the CT/LISS nozzle clearance. The data show that the existing garter spring detection transmit coil and the widely spaced gap receive coil can be used to measure the distance from the PT OD to the LISS nozzle, for distances ≤ 50 mm. The RFEC probe is comparatively insensitive to the presence of garter spring spacers, PT wall thickness variations, and PT constrictions. (A constriction is a region where both PT diameter and wall thickness change relatively abruptly over ≈50 mm axially.) Although the RFEC signal is sensitive to PT/CT gap, the amplitude of the signal due to the LISS nozzle is unaffected by PT/CT gap and the two responses can be separated by their spatial characterisitics.

Equipment: A photograph of the test setup is given in Figure 2. In this photograph, a full length uniform PT is shown with a short section of CT. Phenolic clamps and screws are seen holding the CT in position relative to the PT. A LISS nozzle mock-up was suspended above or below the CT by an acrylic rod. When testing the response to PT constrictions and wall thickness variations, the PT was replaced by a PT with a constriction manufactured at its midpoint, and by a tapered PT respectively. A photograph of the mock-up head is given in Figure 3. The mock-up head is constructed from a stainless steel tube.

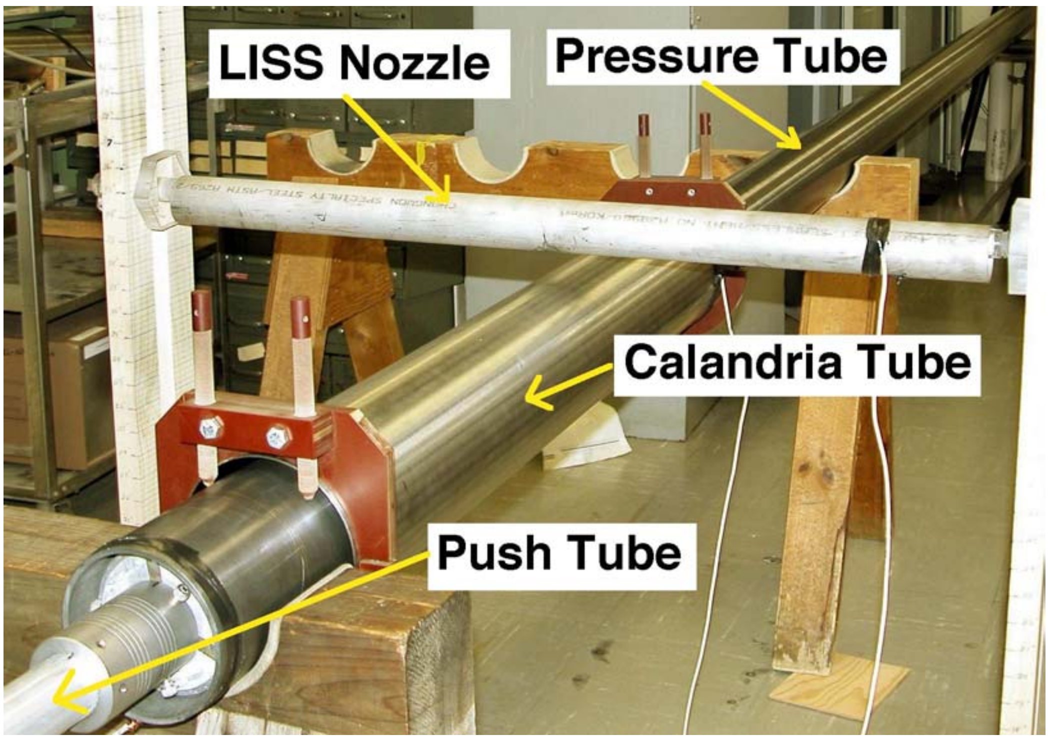

Figure 2: *Overview of Test Setup*

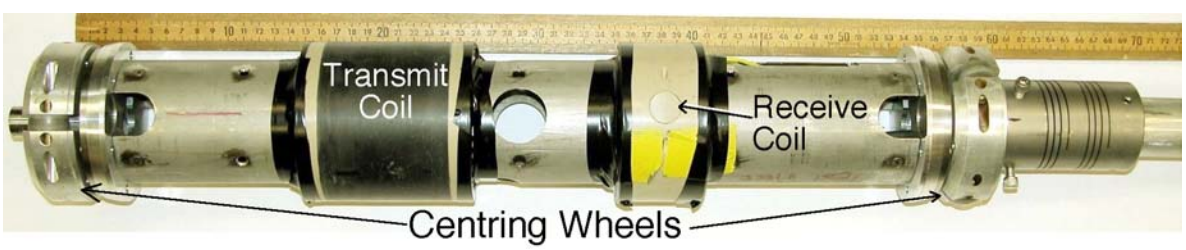

Figure 3: *Photograph of Test Probes*

In current CANDU reactors, LISS nozzles are manufactured from Zircaloy-2. For the work reported here, a 51 mm OD, 3 mm wall thickness, 304 stainless steel tube was used. This tube is not ferromagnetic and has the same electrical resistivity as Zircaloy-2 (72 $\mu\Omega\cdot$cm).

An R/D Tech TC5700 eddy current instrument equipped with a Remote Field module was used. The dual transmitter push-pull configuration was used to maximize the power available to the transmit coil. Two frequencies were used (f and $2\cdot f$), each driven equally at 300 mA_{rms}. The pair of drive frequencies allowed for multi-frequency mixing to reduce the effect of probe wobble. The receivers for both frequencies were configured for a gain of 86 dB and a bandwidth of 20 Hz. Time based acquisitions were performed at a rate of 100 samples/second.

Spacing and Frequency Selection: With the LISS nozzle held constant at ≈30 mm from the CT and the CT concentric with the PT, coil spacing and drive frequency were varied over 80 mm →220 mm and 1 kHz → 4 kHz respectively. One measure of overall performance used to assess the impact of coil separation is the magnitude of the liftoff signal projected onto the LISS nozzle response. A contour plot of this factor is shown in Figure 4. This contour plot was used as a guide to a refined search that established the optimum spacing at 140 mm with a drive frequency of 1.9 kHz. A second frequency at 3.8 kHz was used for mixing.

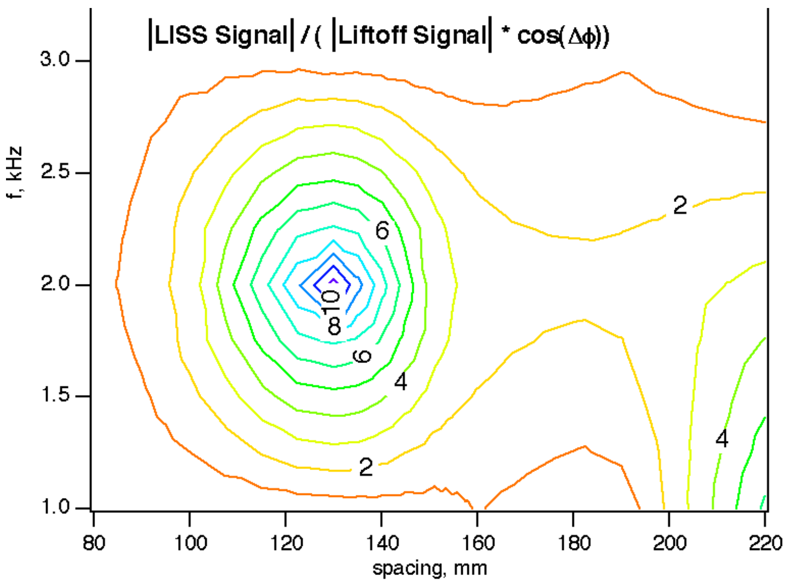

Figure 4: *Contour Plot of Performance Factor, Standard Transmit Coil*

In addition to the above two-parameter search, single-parameter searches were carried out to find the optimum frequencies for use with coil spacings of 166 mm and 200 mm. These spacings were considered because the 166 mm spacing is in use with present AFCIS heads and the 200 mm spacing is being considered for future designs. With a 166 mm spacing, the optimum frequency is 1.7 kHz (with 3.4 kHz for mixing). With a 200 mm spacing, the optimum frequency is 1.5 kHz (with 3.0 kHz for mixing). Given that the 166 mm spacing is close to the optimum, the remaining measurements were performed primarily with this spacing. Signal strength with the 200 mm spacing is about 2/3 that at the 166 mm spacing.

For our probe to be classified as a remote field probe, the flux density outside of the CT near the receive coil must exceed the flux density inside the PT near the receive coil. This was confirmed using the MagNet finite element code [7]. The magnitude of the flux density, |B|, just inside the PT (52 mm inside radius) and a few millimetres outside of the CT (65 mm outside radius) was calculated and is plotted in Figure 5. The plot shows RFEC operation occurs when coils spacing exceeds 110 mm.

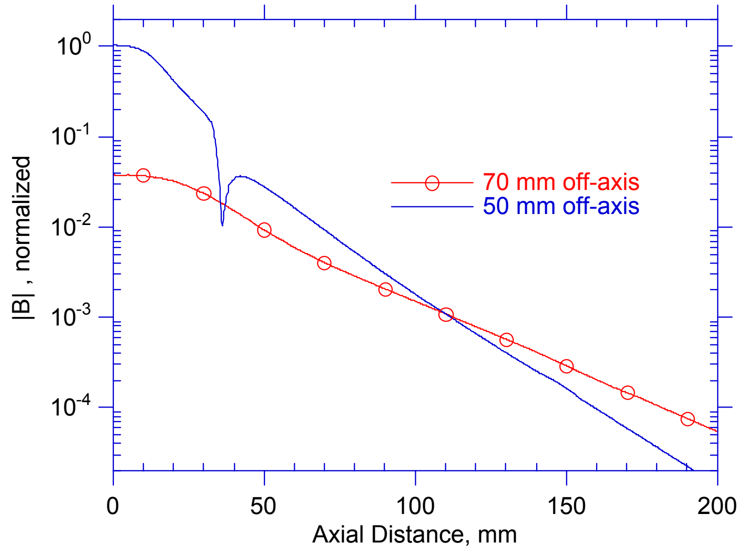

Figure 5: *Magnetic Flux Density Inside and Outside of PT/CT, Focused Transmit Coil*

LISS Nozzle Clearance: The distance from the PT/CT to the LISS nozzle was varied to establish a relationship between the signal amplitude and the distance to the LISS nozzle. The measurements were made with a) concentric PT – CT tubes, b) PT/CT contact at the 6 o'clock position, and c) PT/CT contact at the 12 o'clock position. Coil spacing was set to the 140 mm optimum and at the 166 mm spacing of the present AFCIS head. It was found that the position of the CT had negligible effect on the amplitude of the LISS nozzle signal. Further, the relationship between LISS nozzle signal amplitude to the distance from the nozzle to the PT OD is a simple exponential. Data from this group of measurements are summarized in Figure 6. Measurement of LISS nozzle distance to 50 mm was possible as evidenced by the agreement between measured data and the exponential curve fit. (The distance is from PT OD to LISS nozzle OD.)

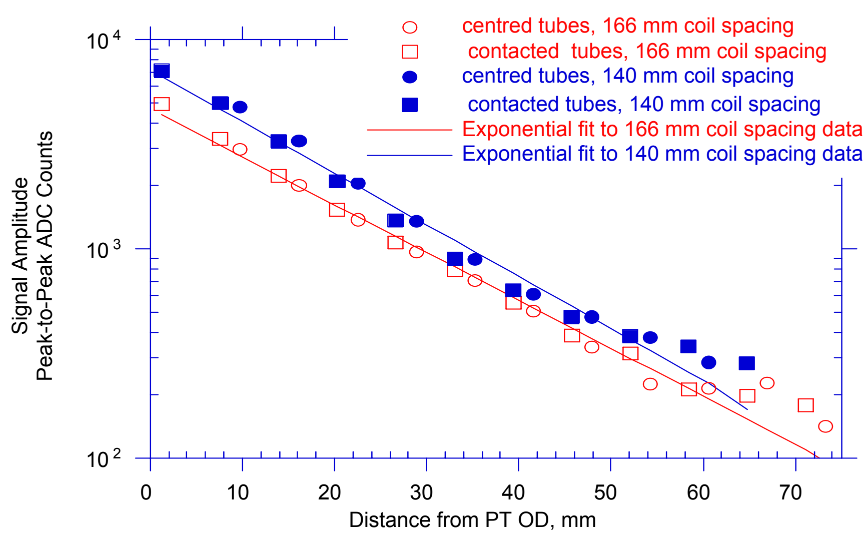

Figure 6: *RFEC Amplitude versus Distance from LISS Nozzle to PT OD*

PT/CT Gap: In Figure 7, the response to a 17 mm change in gap and to a LISS nozzle 20 mm from the PT OD are compared. Although the shape of the signals differ when viewed as

Lissajous plots, it is possible that noise and in-channel distortions could make it difficult to differentiate between the two sources of signal response.

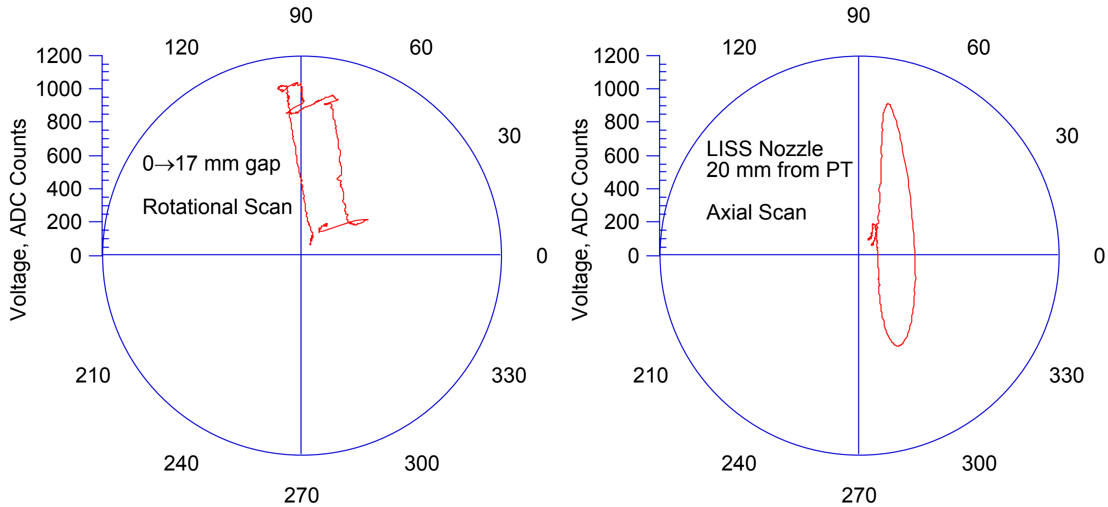

Figure 7: *Lissajous Plots for Response to Gap and LISS Nozzle*

Fortunately, during an axial scan without head rotation, the PT/CT gap should never vary as rapidly as the response produced by a LISS nozzle. Axial-only scanning is the expected method of use for the probe. In the data presented above, and in what follows, the gap signal was produced by rotating the head. The resulting gap variation is much more rapid than is expected for axial scans. As seen in Figure 8, a comparison of the comparatively rapid rotational gap scan to the axial LISS nozzle scan shows a significant difference in the spatial characteristics of the two indications. This difference would be greater for an axial-only scan where the gap would change more gradually.

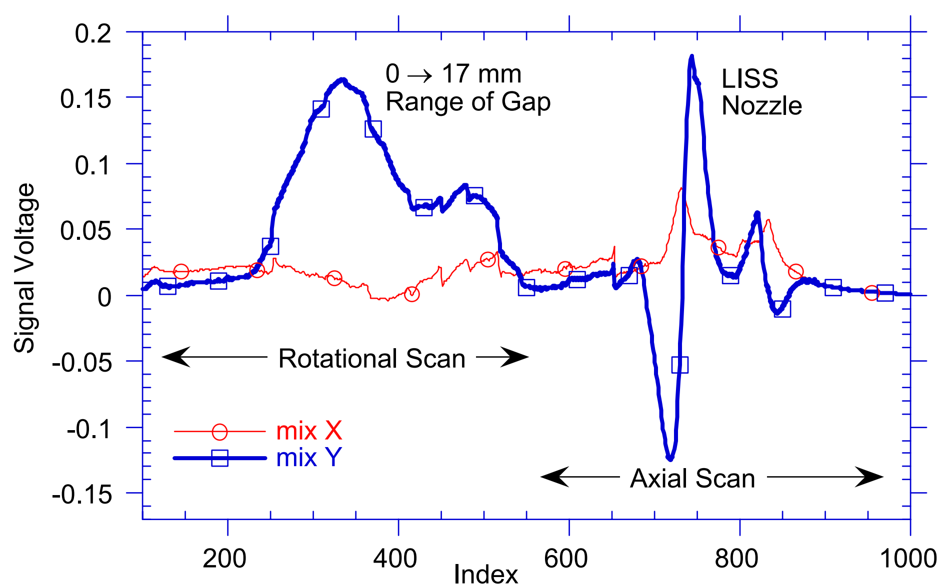

Figure 8: *Gap and LISS Signals, Time-Based Acquisition*

Garter Spring, Constriction, and Wall Thickness: In addition to gap and liftoff, other factors known to influence eddy current inspection of fuel channels are the presence of garter spring spacers, constrictions in the PT where both diameter and wall thickness change relatively abruptly, and general changes in PT wall thickness. To determine the sensitivity to these factors, measurements were made using garter springs, using a PT with a manufactured constriction, and using a tapered PT that had both diameter and wall thickness variations representative of advanced life PTs. The constriction was 50 mm long with a 300 µm reduction in diameter and 20 µm reduction in wall thickness. The tapered PT had an inside diameter ranging from 104 mm to 108 mm and the corresponding wall thickness ranged from 4.13 mm to 3.9 mm. None of these measurements showed any significant interference to the measurement of LISS nozzle distance from the PT OD. In fact, it was not possible to detect the presence of a garter spring with the RFEC probe in its current configuration.

The impact of the constriction, PT wall thickness variations, and PT diameter variations is summarized in Figure 9.

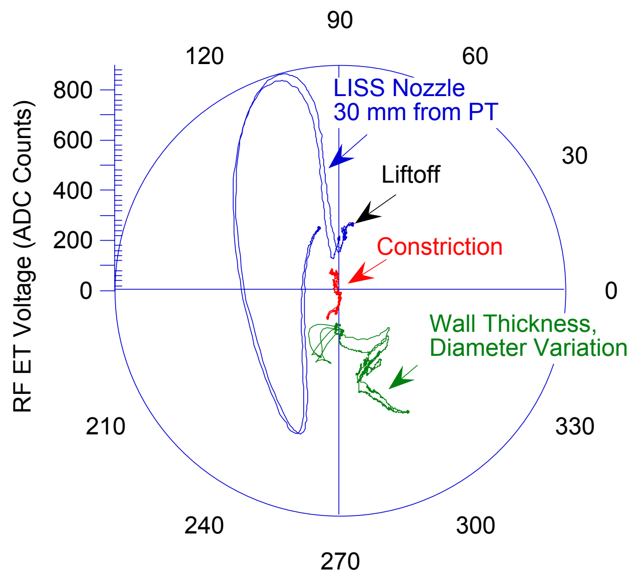

Figure 9: *Lissajous Plots of Signal from LISS Nozzle and Various Noise Sources*

Discussion: With the restriction that existing AFCIS probe coils and coil orientation be maintained, the optimum coil spacing for RFEC measurement of LISS nozzle position was found (140 mm). This optimum is sufficiently close to the present design spacing of 166 mm that the existing design can be used with only a small reduction in performance.

Existing AFCIS heads can measure LISS nozzle to PT OD distance out to 50 mm from PT OD. The relationship between signal amplitude and nozzle distance is a simple exponential. Of the potential interfering factors, only liftoff and PT/CT gap produce significant signals. Liftoff is effectively suppressed using multi-frequency mixing. The response to PT/CT gap variations can be separated from the LISS nozzle signal by considering the spatial characteristics of the two responses.

It should be possible to implement the RFEC measurement of LISS nozzle position without making changes to the AFCIS heads or trunk-line cabling. The only requirement is a RFEC instrument (module) and appropriate interconnections at the instrument. LISS nozzle position could then be measured during normal fuel channel inspections, with only a small incremental effort.

References:

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