[18] ANSYS Release 13.0, (2010) CFD Software ANSYS Inc. USA,

[19] Kim K. T., Kim H. K., and Yoon K. H., (1998) Development of a methodology for In-Reactor Fuel Rod Supporting Condition Prediction", (JOKNS), Volume 28, No. 1,.

Nuclear Power Plant Surveillance Monitoring by Vibration and Acoustic Signals

Ghulam Mustafa

ABSTRACT

The purpose of this paper is to provide analytical tools for the analysis of the vibration of structure exposed to a fluid flow. Since the paper is basically emphasis on the sound and acoustical analysis of some experimental results, so it assumes some knowledge of acoustic analysis and structural vibration.

The paper highlights the causes of loose parts and the economic impacts of the detection of these detach parts. The most common consequence of loose parts is the ageing of the material. Steam generator tubes can also be broken or blocked. The Loose Parts Monitoring Technique employ vibration accelerometers for the detection of acoustic waves or bursts produced through the metal-metal impact of the loose parts with the structure surface.

The paper emphasized on the basic techniques to localized the loose parts and signals analysis. The characteristics of metal-metal impact are calculated with the help of Hertz impact theory, plate wave propagation theory, Lamb diagram of sound wave dispersion modes and sound intensity attenuation calculations.

Keywords: Vibration Analysis, Plant Surveillance, Loose Parts Monitoring, Structural Integrity and Flow Induced Vibration

Introduction:

A loose part is an object, which has been left in the system during maintenance, or an internal component dislodged during operations. Loose parts are transported by the flow of the coolant pumps, in the primary loop consisting of the reactor pressure vessel, the main coolant pumps, and the steam generator reactor cooling piping. The presence of a loose (i.e., disengaged and/or drifting) object in the primary coolant system can be indicative of degraded reactor safety resulting from failure or weakening of a safety-related Component. A loose part, whether it is from a failed or weakened component or from an item inadvertently left in the primary system during construction, refueling, or maintenance, can contribute to component damage and material wear by frequent impacting with other parts in the system. A loose part can pose a serious threat of partial flow blockage with attendant departure from nucleate boiling (DNB) which in turn could result in failure of fuel cladding. In addition, a loose part increases the potential for control rod jamming and for accumulation of increased levels of radioactive crud in the primary system.

Related Danger:

The loose parts circulate along with the coolant flow and may cause blockage in the reactor core or stream generator tubes. The flow blockage core has very serious consequences since it may load to partial fuel melt down. Stream generator tank looses would also cause expensive plant outage and repair cost. The metallic loose parts circulating in the coolant flow loops of nuclear and thermal power plants are a serious hazard for the plant safety and cost economics. These objects may cause partial coolant blockage through the boiler tubes or reactor core resulting in the failure of boiler tubes or reactor fuel. Widespread component damage has been reported internationally in power plants due to this phenomenon. In nuclear industry, the safety regulations make it mandatory to detect, identify and localize the loose parts in nuclear power plants. Due to this in every pressurized nuclear power plant in advanced country have this system.

Basic Task:

Our task is to detect loose parts, which occur in the primary coolant loop before they can cause significant damage to reactor internals. As a result of metal-metal impact a ringing sound is produced which propagates through the reactor structure. The piezoelectric accelerometer sensors are located at key location detect this sound, and with the help of detailed analysis of the sensors signals, the location of the loose parts are determined. The constraints for our detail analysis are capable of detecting metallic loose parts with high accuracy.

Literature Review:

The paper especially focuses on theoretical and analytical solutions to the problems of Loose Parts Monitoring techniques, possibly combined with other traditional computing tools. Dr. C. W. Mayo & J. M. Doster (December 1995), the purpose of this research was to establish quantitative relationships between the detected reactor loose part signal properties and the loose part damage potential. Two important open issues concerning the validity of Hertz impact theory for in-water reactor loose part impact and for the typical range of loose part impact energy were clarified experimentally. A linear correlation between plastic deformation volume and impact energy in a single impact was verified for different impact contact shapes. As the internal structures rest intermittently on the reactor vessel, the impact could originate from them, with the waveforms transmitted via the structure support.

The Loose Parts Monitoring technique employ piezo-electric vibration accelerometers for the detection of acoustic waves or bursts produced through the metal-metal impact of the loose parts with the structure surface. This paper describes the Localization of the loose parts (impact location) by rigorous analyses of sensor signals by applying various techniques of band pass filtering, acoustic modeling, and signal frequency spectrum analysis, probability distributions and cross correlation. The characteristics of metal-metal impact are calculated with the help of Hertz impact theory, plate wave propagation theory, Lamb diagram of sound wave dispersion modes and sound intensity attenuation calculations. The loose part mass is determined by comparing measured and calculated burst central frequencies and impact contact times, and the loose part impact energy is estimated by a comparison of accelerometer signal magnitude with calculated plate wave acceleration. The triangulation and the hyperbola intersection methods obtain localization of the loose part.

Loose parts localization Techniques:

The operation of a reactor is generally associated with background noise and sound events caused by the operation. These are caused by the coolant flow, by the discrete frequency sound from pumps and by the operation of other components such as valves and control elements. Additional structure-borne sound signals are generated when detached parts meet the inner walls of the reactor pressure vessel and internal fittings or when loose parts knock against internal fittings within the boundary. These individual sound events, the so-called bursts, must be unambiguously distinguished from the background noise and located. For this purpose, the intensity of the structure -borne sound signals measured is monitored in a specific frequency range. When specified limiting amplitude values are exceeded, an event alarm is emitted. In addition, it is possible to listen to the background noise and to analyze and record it that regular intervals in order to provide reference measurements so that, when the sound events cannot be unambiguously assessed, the noise pattern and the signal pattern can be compared with the reference patterns in order to from a judgment.

Delay time differences between associated sound patterns, as measured by sensors positioned at different points, are used as the criterion for distinguishing between detached and loose parts, i.e. between stationary and spatially varying impact locations. in the case of detached parts, statistically varying values occur. Localization of loose parts using accelerometer sensor signals can be very difficult in practice. In some cases the loose part impact may be registered on one sensor alone and in such cases no conclusive results about the source location can be obtained. In other instance where bursts in several monitoring channels appear, the localization methods using time lags between bursts in different signals sometimes give erroneous results due to a large noise contamination. The main sources of error in the localization of loose parts are as follows:

The sound waves emitted from the impacting loose part have multiple frequency components. These waves having different frequencies travel with different velocities. It is therefore very difficult to accurately determine the relative delay time in different LPMS sensor signals. To resolve this problem an average sound wave velocity is used to calculate the transit-time, i.e. time required for the sound to travel from the source to the sensor. The wave velocity in the S0 and A0 modes is obtained with the help of Lamb diagram.
The sound waves traveling from the source (loose part) to the sensors undergo attenuation in intensity while traveling through the metallic structure. The attenuation in sound energy is non-linear and depends strongly upon the path geometry. It is therefore expected that the signals from different LPMS sensors would have marked difference in their time and frequency composition.
The irregular boundaries of the reactor structure, viz. pipe branching, elbows etc. cause distortions in sound wave propagation, which contribute towards the errors in loose part localization.

Plate Wave Transitions:

For bending waves which is the dominant mode for plate stress wave transmission. The propagation speed of the wave is a function of both the wave frequency and the plate thickness. Bending waves therefore exhibit dispersion, i.e. different frequencies propagate at different velocities resulting in a wave shape, which is a function of distance. The observed time required for bending wave to travel over a given distance reflects a group velocity that is a function of dominant frequencies in the detected signal. The dependence on velocity means that the wave propagation speed is different in component of different thickness. Typical wave velocities for LPMS signals of interest lie in the range 1-3 x 10^{3} ms -1.

Theory of Loose Parts Impact:

Hertz theory defines the motion of initial point of contact between a solid metal object and an infinite plate as a half sine function with half period and amplitude corresponding to the impact contact time and the peak displacement during the time of contact. The impacting object mass, velocity governs these parameters at the time of initial contact, and radius of curvature.
The equations to define peak displacement, velocity acceleration, and force for impacting object are given from equation 1-6.

$$D_{\max} = k_h (mv^2)^{0.4} R^{-0.2} \quad \text{-----------1}$$

$$V_{\max} = \pi k_h / t_h (mv^2)^{0.4} R^{-0.2} \quad \text{-------2}$$

$$A_{\max} = k_h^{-1} m^{-0.4} v^{1.2} R^{0.2} \quad \text{-----------3}$$

$$F_{\max} = k_h^{-1} (mv^2)^{0.6} R^{0.2} \quad \text{-----------4}$$

$$t_h = \pi k_h m^{0.4} v^{-0.2} R^{-0.2} \quad \text{-----------5}$$

$$k_h = ((1-\nu_1{}^2)/E_1 + (1-\nu_2{}^2)/E_2)^{0.4}$$ ---6

m = mass of the object

v = initial velocity of the object

R = radius of curvature at point of contact

ν1, E1 = Poisson Ratio and Young's modulus for plate,

ν2, E2 = Poisson Ratio and Young's modulus for the object

Plate Wave Frequency:

The initial plate motion at point of impact is translated into a cylindrical wave that expands away from the impact location. These waves are attenuated as they travel from source to sensor. The attenuation is a complex phenomenon and depends upon bends in structural material the attenuated waves are sensed by the sensors. The initial plate motion at point of impact due to the impact force is translated into a cylindrical wave that expands away from the impact location. This wave has a different shape and frequency content than the initial half-sine motion at the point of contact. As the plate wave propagates through reactor structure it is detected as the acceleration signals by the acoustic sensors of plant LPMS. The magnitude and frequency of the acceleration signal from acoustic sensors therefore correspond to the plate wave intensity and frequency. The relation that governs the magnitude of the plate wave acceleration at the impact location is

$$A_{plate} = F_{\max} / M_{eff}$$ -----------7

Where F-max is the peak impact force and M-eff is an effective mass of the plate volume, which is in contact with the impacting object at the time of impact. The relation gives M-eff

$$M_{eff} = \pi (c_b t_h)^2 h \rho_{steel}$$ (2)

Where, h = plate thickness,

Cb = bending wave velocity

ρSteel = density of steel

Sensor Triangulation Technique:

The loose parts localization technique incorporates the circle intersection method, which was introduced at Berkeley Nuclear Laboratories. In this method the triangulation technique of the arrival times of the burst event at various sensor locations is utilized to determine the distance between loose part and the sensors, as well as angles of incidence. Any loose part trapped in the pressure boundary of a nuclear power plant would generate acoustic waves. These waves will be received at different times by acoustic sensors located at different locations on the structure surface. The difference in the arrival times of an acoustic wave at the sensors locations defines the difference in distances of the emission source form these sensors. It can be shown that the emission source lies on a hyperbola defined by the difference in arrival time with the two sensors as foci. Two differences in arrival time from an array of three sensors define a pair of hyperbolae at whose point of intersection the emission source is located.

Method of solution:

The different in arrival time of an acoustic-emission wave at a pair of sensors defines the difference in distance of the emission source from the two sensors. It can be easily shown that the emission source lies on a hyperbola defined by the difference in arrival time with the two sensors as foci by the difference in arrival time from an array of three sensors define a pair of

hyperbola, in terms of the observed differences in arrival time, involve square roots making an analytic solution extremely difficult. The analytic solution for source location is however simplified when an alternative approach, similar to an Apollonian construction, is employed.
Consider an arbitrary three sensors array with sensors located at points S0 (0, 0), S1 (X1, Y1) and S2 (X2, Y2). An acoustic emission source at P(x, y), a distance r from S0, will give rise to path difference δ□ and δ2 defined by
δ1= PS1 – PS0 = t1 x v and
δ2 = PS2 – PS0 = t2 x v
S2 (X2, Y2)
Where v is the velocity of propagation in the material and t1 and t2 are the differences in arrival time measured for sensors S1 – S0 and S2 – S0 respectively.
The acoustic emission source at P(x, y) is located at the point of intersection of the circles about S0, S1 and S2 as centers with radii r, r + δ□ and r + δ2 respectively.
The equation of the three circles is respectively:
X2+ Y2 = r2
(X- X1)2 + (Y – Y1)2 = (r + δ□)2
(X- X2)2 +(Y – Y2)2 = (r + δ2)2
Taking the first equation from the other two in turn:
2xx1 + 2yy1 = (x12 + y12 – δ□2) – 2r δ□
2xx2 + 2yy2 = (x22 + y22 - δ22) – 2r δ2
Changing to polar coordinates these become respectively
2r(x1 cosθ + y1sinθ + δ□) = A1
And
2r(x2 cosθ + y2 sinθ + δ2) = A2
Where
A1 = x12 + y12 - δ□2
A2 = x22 + y22 - δ22
Therefore for (x1 cosθ + y1 sinθ + δ□) $\neq$ 0 $\neq$ (x2 cosθ + y2 sinθ + δ2) the polar coordinate equations yield

$$r = \frac{A_1}{2(x_1 \cos\theta + y_1 \sin\theta + \delta_1)}$$

$$= \frac{A_2}{2(x_2 \cos\theta + y_2 \sin\theta + \delta_2)}$$

From which it follows
(A1x1 – A2x2) cosθ + (A1 y2 – A2y1) sinθ = A2 δ□ – A1 δ2.
Dividing through this equation by the term (A1x2 – A2x1)2 + (A1y2 – A2y1)21/2 yields.

$$\frac{(A_1x_2 - A_2x_1)\cos\theta}{[(A_1x_2 - A_2x_1)^2 + (A_1y_2 - A_2y_1)^2]^{1/2}}$$

$$+ \frac{(A_1y_2 - A_2y_1)\sin\theta}{[(A_1x_2 - A_2x_1)^2 + (A_1y_2 - A_2y_1)^2]^{1/2}}$$

$$= \frac{A_2\delta_{1-} A_2\delta_1}{[(A_1x_2 - A_2x_1)^2 + (A_1y_2 - A_2y_1)^2]^{1/2}}$$

Since, in this form, the coefficient of the cosθ and sinθ terms are less than unity, the equation takes the form cos (θ -ϕ) = K. Where

K= (A2 δ□ – A1 δ2)/ B
B = (A1x2 – A2x1)2 + (A1y2 – A2y1)21/2
And

$$\tan\phi = \frac{(A_1 y_2 - A_2 y_1)}{(A_1 x_2 - A_2 x)_1}$$

Since both the numerator in the term for tan θ can be determined exactly from the known positions of the sensors (x1, y1) and (x2, y2), the measured emission arrival time difference t1 and t2 and the propagation velocity v, the angle θ is defined uniquely in the range -π to +π. Let ϕ = α + 2mπ, for m + 0, +, 1 +, 2.

By definition the term β is positive. Hence there are two solutions for (θ -ϕ) in the range -π to +π in the equation cos (θ -ϕ) = K: if the term (A2δ□– A1δ2) is positive the equation has a solution in both the 1st and 4th quadrants; and if the term (A2δ□ – A1 δ2) is negative the equation has a solution in both the 2nd and 3rd quadrants. That is if

β = cos-1 /K/ then

(θ - ϕ) = β + 2nπ or - β + 2nπ for n = 0, +, 1 +, 2

It follows from this equation and that for ϕ that

0 = (α + β) + 2mπ, for m = 0, +, 1 +, 2

That is θ has two solutions in the range -π to +π.

A value of θ must yield r positive in the derivation for r shown earlier, in order to be a valid solution. The Cartesian coordinates of the emission source location can be then derived. In the large majority of cases, when only one value of θ is valid for a given pair (t1, t2) of time difference, the solution for the source location is unique. When two solutions of θ exist for a given (t1, t2) pair the corresponding source location is ambiguous, with locations corresponding to the two possible points of intersection of the hyperbolae defined by the time difference t1 and t2 observed by sensors S0, S1 and S2. Such ambiguous are ignored by location method involving iterative procedures.

In order to resolve the ambiguous solutions it is necessary to use a fourth sensor S3, located at the point (x3, y3) say, and compare the difference in arrival time t3, measured for sensors S3 – S0 with that calculated for the source location. This check also validates events located by three sensors.

Results and Discussion:

A large number of acoustic bursts were generated in the experimental measurements by applying the impact hammer to the surface of the tank with variable force and at variable distance from the accelerometers sensors. The coordinates of the three sensors were also varied in two-dimensional geometry over the radial and axial planes for these measurements.

The first graph displays the force signal of the impact hammer, whereas the three other graphs show the real-time behavior of the three acoustic burst signals generated as a result of the impact. The coordinates of acoustic sensors and impact point (in meters) on the cylinder for the particular measurement are given below:

Sensor #1 (S0): Reference sensor ;(0, 0)
Sensor #2 (S1) :(0, 0.4)
Sensor #3 (S2) :(1.4, 0)

Hammer (h) :(1, 0.2)
Fig. 1 is a graphical representation of these coordinates showing the impact location and the acoustic sensors.
It is evident that striking the impact hammer on the tank surface produces an impact force of the form of a sharp pulse of a total duration of 0.23 ms. The advantage of such sharp pulse signal is that it can excite wide range of acoustic frequencies along the surface of the cylinder. This fact is also evident from the frequency spectrum of the impact hammer shown in Fig. 3. This frequency spectrum is that of a typical bandwidth-limited white noise signal. The sharp peak at 6.6 KHz is the hammer resonance frequency. The real-time representation of the bursts signals detected by sensors S0-S2 shown in Fig. 2 is that of typical exponentially decaying bursts. The frequency spectra of these bursts show that the burst signals have multiple frequency components. The peak burst frequency varies between 1.1 KHz to 1.25 KHz for the three sensors signals. The frequency spectra of the bursts signals show that the sound waves detected by the three sensors have nearly identical frequency composition. It is therefore expected that the relative velocities of these sound waves for the three bursts do not vary much. This fact facilitates defining a common velocity of sound waves in the calculation algorithm.

To demonstrate the effectiveness of the algorithm for automatic detection of acoustic bursts and accurate computation of relative burst arrival times for the three sensors. The figure shows the early part of the acoustic bursts signals against the signal background. The automatic burst arrival time algorithm based on statistical analysis calculated the delay times between the hammer impact signal and acoustic sensor signals as below.
Delay between hammer and S0 signals: 0.33 ms
Delay between hammer and S1 signals: 0.3 ms
Delay between hammer and S2 signals: 0.195 ms.
It is evident from the zoomed display graphs that at the calculated burst arrival times for all sensors the sensors signals show a definite deviation from the signal background noise. It is therefore confirmed by actual measurements that the algorithm for automatic detection of burst arrival is capable of Impact Location Source location is based on the assumption that the actual acoustical paths to the sensors are the walls of the pressure-retaining boundary, and that the degree of acoustical transmission of sound in water is much less than that in the solid boundaries. Impact location is derived from the order of arrival and relative delay time of signals from three different sensors using hyperbolic intersection. The location process requires three steps of the burst over the background noise. This feature of early burst arrival detection results in high precision of location calculations of the loose parts.

Effect of delay time:

Effect of Delay Time Error on LP Location the calculations of distance and angle is quite sensitive to a change in the relative time delays between successive sensors signals. This is partly due to the fact that in the calculation algorithm the sound velocity is also calculated from the time delays.

Effect of sound wave velocity:

In order to determine the sensitivity of the calculations of loose parts location on the velocity of sound waves emitted by the acoustic burst, the calculations of distance and angle of incidence were made over a range of sound velocities between 1700 m/s to 3400 m/s. For a 100% change in sound velocity, between 1700 m/s and 3400 m/s, the variation in r4 is only 7%, whereas the distances r1 and r2 vary by a factor of 20% for the same range of sound velocities. The distance r3 is negative for all values of the velocity, and its value is very sensitive to the change in sound velocity. R3 is therefore not acceptable since it yields negative distance.

Conclusions and Recommendations:

The determination of loose part location (distance and angle) within reactor pressure boundary by analysis of acoustic signals is a complex problem and involves application of theories of sound wave transmission, attenuation and reflection through reactor structures. Due to high velocities of sound waves (~ 5 km/s), the acoustic signals need to be analyzed with microsecond resolution. Also sound waves of different frequencies travel at different speeds, which make accurate determination of the relative delay times very difficult. The computation of distance and angle is done with the help of the Berkeley Method of 3-sensors parabolas triangulation technique. Significant improvements in LP location calculations were achieved by reducing errors in sound velocity determination, burst arrival times and angle of incidence. It has been shown that the loose parts localization algorithm is capable of automatically detecting the arrival times of acoustic bursts with high precision. This capability is very helpful in accurate localization of loose parts, and the loose parts can be localized within ± 20 cm accuracy. The angle of the loose parts impact can also be determined accurately. A general method has been developed for calculating the location, in two dimensions, of an acoustic emission source. The method yields an exact solution for any three-sensor configuration. It has been found that the most precise source location for a given timing capability is achieved for emission sources within the area bounded by the sensors.

This paper gives the details of localization of the trapped loose part by detailed analysis of the sensor signals from the plant loose parts monitoring system. It models the metal-metal impact with the help of Hertz impact theory, theory of plate waves propagation, Lamb diagram for modes of sound wave dispersion through reactor structure, and sound intensity attenuation calculations. Loose part mass is determined by comparing measured and calculated burst central frequencies and impact contact times, and the loose part impact energy is estimated by a comparison of accelerometer signal magnitude with calculated plate wave acceleration. The routines of signal statistical analysis, frequency spectrum computation, and delay-time by cross correlation analysis, circle intersection method, and narrow-band filtering has been developed. From the detail analysis of the acquired data we saw that the velocity of the sound propagated by the impact hammer depends upon the force of impact with which hammer might be struck. The delay time of the signals must be calculated very carefully because all our calculation depends upon these calculations. The very minor mistake can change our results in very beyond the exact values.