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Technical Support Package

Ultrasonic Measurement of Bending of Bolts

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Technical Support Package

for

ULTRASONIC MEASUREMENT OF BENDING OF BOLTS

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Measurement of Fastener Bending Using an Ultrasonic Method and a Modified Fastener End

Introduction

The threaded end of a fastener is modified (to a stepped end) to provide reflective surfaces for an ultrasonic beam. An ultrasonic pulse is generated by an ultrasonic transducer coupled to the other end of the fastener. This pulse travels to and is reflected by the stepped end, which has multiple reflective surfaces. After reflection from each of the surfaces as a separate pulse, the pulses travel back to and are electronically received by the transducer. Each of the reflective surfaces provides a distinct pulse return-trip travel time. Adjacent reflective surfaces are separated by a distance which allows the reflected pulses to be separated from one another. Thus, a pulse reflected from any of the reflective surfaces does not overlap with a pulse reflected by any of the other surfaces. One of the reflective surfaces is symmetrical about the central fastener axis. All other reflective surfaces are of some shape and size. These surfaces are oriented and located identically about the central axis, except for their angular location. The angle formed by the radial planes passing through the centers of any two adjacent surfaces is the same. Under bending, the path length of the pulse reflected by each surface may change. This change in path length and the change in velocity occurring due to stress may result in a change in pulse travel time. Pulse travel time is further processed to compute an ultrasonic bending parameter. During load calibration, a characteristic curve correlating the ultrasonic bending parameter to the applied bending (load, dimensional or angular measurement) is established for a given fastener in a given structure. Characteristics are used to determine bending from the measured ultrasonic bending parameter for an identical fastener in an identical structure.

Principle

FIGURE 1 shows a fastener experiencing bending. FIGURE 2 shows the ultrasonic beam paths inside the fastener. The reflected beam does not travel the incident beam path for two reasons: Firstly, under bending the reflective end of the fastener becomes nonparallel to the incident end. Thus, the beam hits the reflective end at an angle other than 90 deg. This causes the reflected beam to make a finite angle with the incident beam. Secondly, there is a bending stress gradient in the fastener (as shown in FIG. 3). The compressive stress makes the longitudinal wave travel faster, and tensile stress makes the longitudinal wave travel slower with the change in velocity being proportional to stress. The change in ultrasound velocity over the cross-section results in part of the beam traveling faster. This bends the beam. The beam bends towards the outer bending curvature as shown in FIGURE 3. This in turn results in increased path length and increased pulse travel time. The effect of three regions of the fastener—i.e., the outer bend region, the inner bend region, and the region in the center—on pulse travel time is discussed below.

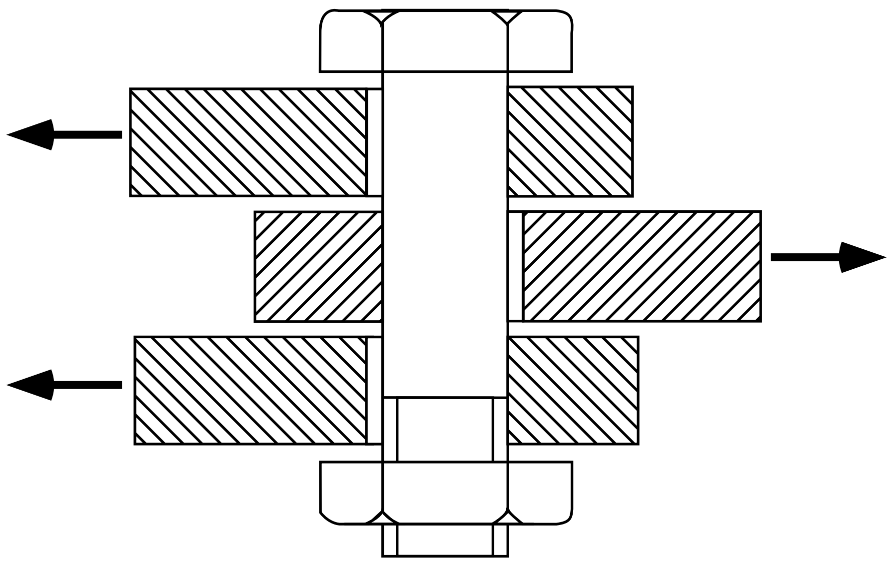

FIG. 1 Fastener in shear and bending

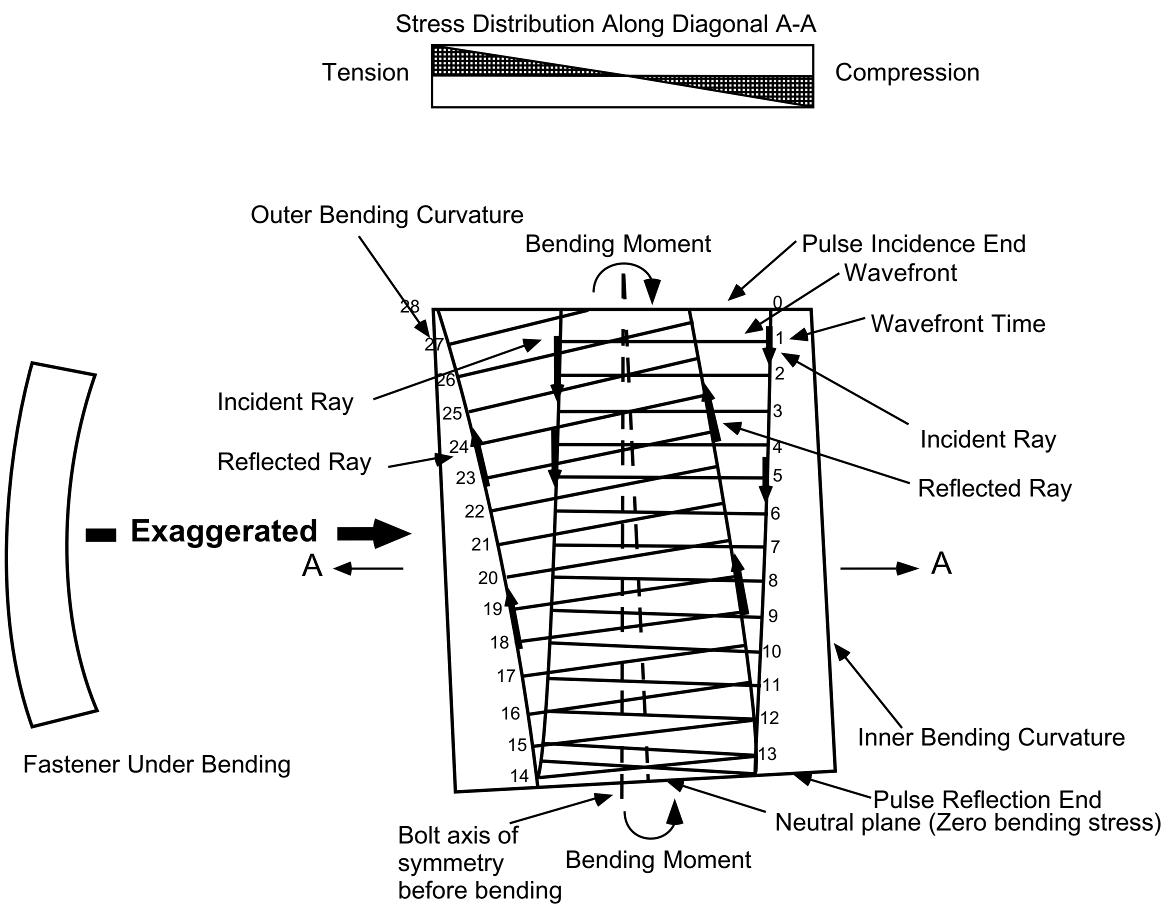

FIG. 2 Beam path

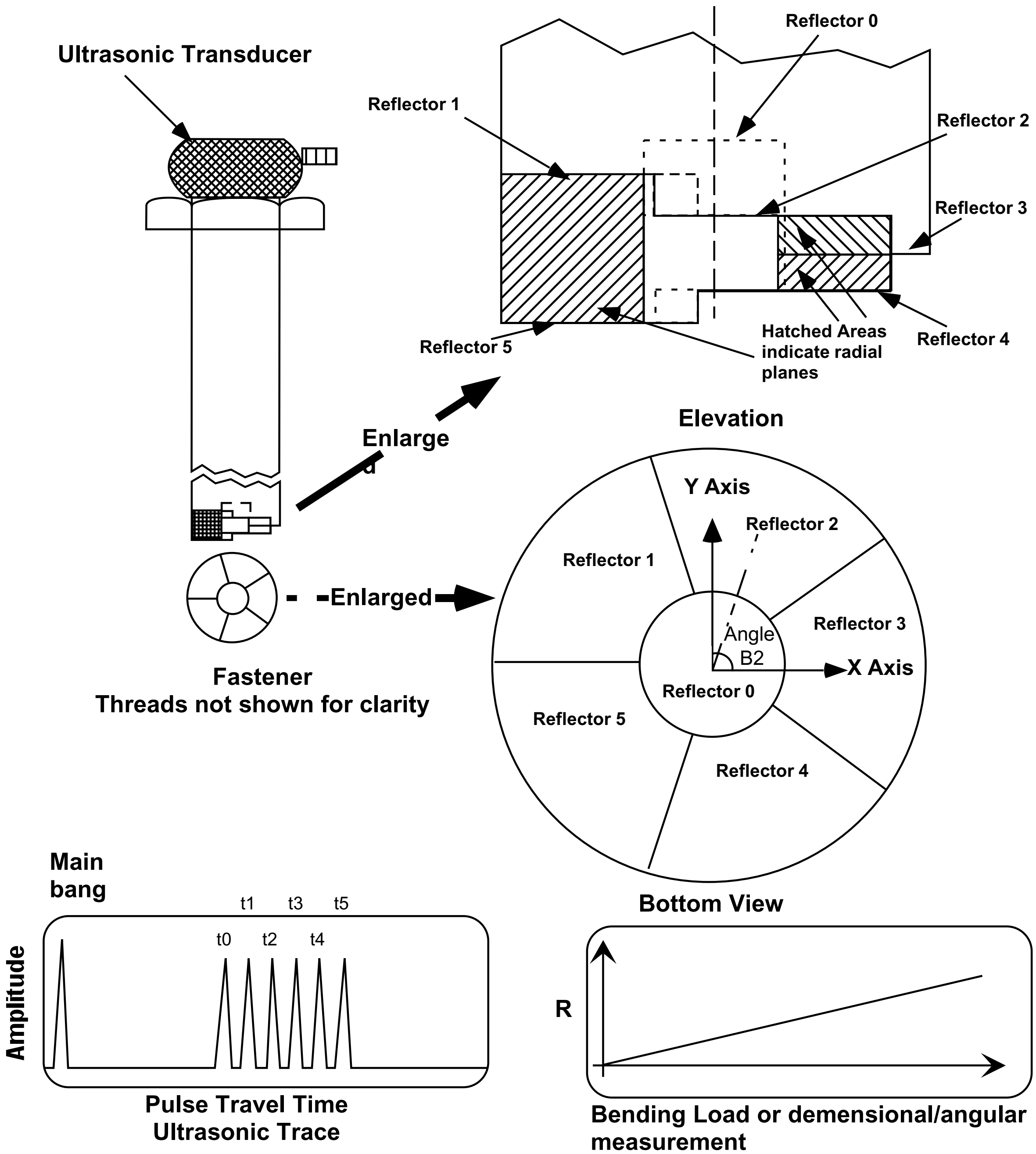

FIG. 3 Modified end of the fastener and ultrasonic echoes from the modified end

In the inner bend region, the effect of bending brings the incident and reflected surfaces closer. This reduces the path length. The inner bend has compressive stress, which increases longitudinal velocity, thus reducing pulse travel time. The compressive stress gradient bends the beam towards the outer bend, leading to a slight increase in path length. The net result for the beam is a decrease in pulse travel time.

In the outer bend region, the effect of bending moves the incident and reflected surfaces away from each other. This increases path length. The outer bend has tensile stress, which decreases longitudinal velocity and increases pulse travel time. The tensile stress gradient bends the beam towards the outer bend, which results in a slight increase in path length. The net result for the beam is an increase in pulse travel time.

Consider two identical incident beams from two regions; one from the inner bend region and one from the outer bend region. The beams are incident at the same radial distance from the axis of the fastener. Under bending, change in pulse travel time is greater for a beam in the outer bend region than in the inner bend region. This is due to the fact that the beam bending and the geometric bending of the fastener have opposing effects on the change in path length in the inner bend region. In the outer bend region, the beam bending and the geometric bending of the fastener increase the path length.

In the center region, the effect of bending moves the incident and reflected surfaces away from each other on the outer bend side and closer to each other on the inner bend side. This decrease in path length on the inner bend side of the center region is canceled by an increase in path length on the outer bend side of the center region. This occurs because the transducer averages the pulses if the path length difference is much smaller than the wavelength of the pulse. The bending stress gradient bends the beam, which results in increased path length. The change in velocity of the beam is very slight because the bending stress is very low in the center. The net result for a beam passing through the center is a very slight increase in pulse travel time.

Since the beam does not return to the same point on the transducer, some signal distortion is inevitable.

MODIFICATION OF THE FASTENER END

One of the fastener and modification configurations is shown in FIGURE 3. The steps, which are square to the fastener longitudinal axis, provide separation of reflected pulses. Area 0 is in the center. Areas 1 to 5 are off center. The number of off-center areas is chosen for a given application. Larger numbers of reflective areas provide better accuracy of bending measurement, but the signal strength reduces because the size of the reflector area reduces. Odd numbers of off-center reflector areas have the advantage over the even numbers of these areas. In the case of even numbers of off-center areas, every offset area has another identical area that is diagonally opposite (180 deg) from it. The two areas essentially provide the same information, except the area close to the outer bend is more sensitive to bending than the area close to the inner bend. Therefore, the even configuration is slightly better than the odd numbered configuration, with half as many reflective areas. If the amount of bending is large, the beam may bend by a large amount not to be reflected by some of the areas. Having diagonally opposite identical areas will allow the beam to be reflected by one of the two diagonal areas for higher bending loads and will allow the bending measurement. For higher bending loads, even numbers of reflective areas may be more appropriate. In another configuration, the diagonally opposite off-center area pairs may be at the same level. The two areas in a pair act as a single area. This configuration will allow relatively higher bending loads to be measured. The center area may or may not be fabricated.

In another configuration, a separately fabricated stepped end can be bonded to the square end of a fastener. In this case, the depth of the shallowest reflector (from the bond line) should be more than the level difference between the shallowest and the deepest reflector.

In yet another configuration, only two off-center areas may be used if the bending plane maintains constant orientation. In this case, the line joining the centers of the two areas should be coincident with the bending plane.

CALCULATION OF ULTRASONIC BENDING PARAMETER AND BENDING

The measurements of the pulse travel time should be temperature compensated.

$$t = t_u(1 - C\Delta T)$$

where

t = compensated travel time

t_u = uncompensated travel time

ΔT = difference between the actual temperature and the standard temperature

C = temperature compensation coefficient

A coordinate system is established as shown in FIGURE 3. For the case shown, the processing of travel time measurements is indicated in the TABLE. Area number is used as a subscript to time variable; e.g., t_o. Both unloaded and loaded measurements are required. The measurement and computation are performed from the left column (A) to the right column (K) in the TABLE. *X* and *Y* are computed in the last two columns. *R* and α are computed as indicated in the table. *R* is referred to as the ultrasonic bending parameter. α is the angle of the bending plane. The ultrasonic bending parameter is computed during a load calibration test for each value of applied bending load. The data of the bending load (or other bending measurement) are plotted against the ultrasonic parameter (FIG. 3). Within certain limits the two correlate. This correlation may not be linear; but a curve, called the characteristic curve, can be fitted through the data. The characteristic curve can be used with the same instrumentation to determine bending from the measurement of the ultrasonic bending parameters in the same or identical fasteners in identical structures.

If the fastener experiences both bending and tensile load, the center reflection area (Area 0 in FIG. 3) can be used to measure the ultrasonic stretch in the bolt. The ultrasonic stretch (δt_0) can be converted to tensile load in the fastener using the characteristic curve for the tensile load.

Computation of Bending Plane Angle, α, and Ultrasonic Bending Parameter, *R*

A	B	C	D	E	F	G	H	I	J	K
Reflector no., i	**Radial Angle**	**Cosine β_i**	**Sine β_i**	**Travel Time Under No Stress, t_i**	**Travel time Under Stress, t'_i**	$\Delta t_i = t_i - t_0$	$\Delta t'_i = t'_i - t'_0$	$\delta\Delta t_i = \Delta t'_i - \Delta t_i$	$\delta\Delta t_i$ cosine β_i	$\delta\Delta t_i$ sine β_i
0	—	—	—	t_0	t'_0	—	—	—	—	—
1	$\beta_1 = 144$			t_1	t'_1	$\Delta t_i = t_i - t_0$	$\Delta t'_1 = t'_1 - t'_0$	$\delta\Delta t_1 = \Delta t'_1 - \Delta t$	$\delta\Delta t_1$ cosine β_1	$\delta\Delta t_1$ sine β_1
2	$\beta_2 = 72$			t_2	t'_2	$\Delta t_2 = t_2 - t_0$	$\Delta t'_2 = t'_2 - t'_0$	$\delta\Delta t_2 = \Delta t'_2 - \Delta t$	$\delta\Delta t_2$ cosine β_2	$\delta\Delta t_2$ sine β_2
3	$\beta_3 = 0$			t_3	t'_3	$\Delta t_3 = t_3 - t_0$	$\Delta t'_3 = t'_3 - t'_0$	$\delta\Delta t_3 = \Delta t'_3 - \Delta t$	$\delta\Delta t_3$ cosine β_3	$\delta\Delta t_3$ sine β_3
4	$\beta_4 = 288$			t_4	t'_4	$\Delta t_4 = t_4 - t_0$	$\Delta t'_4 = t'_4 - t'_0$	$\delta\Delta t_4 = \Delta t'_4 - \Delta t$	$\delta\Delta t_4$ cosine β_4	$\delta\Delta t_4$ sine β_4
5	$\beta_5 = 216$			t_5	t'_5	$\Delta t_5 = t_5 - t_0$	$\Delta t'_5 = t'_5 - t'_0$	$\delta\Delta t_5 = \Delta t'_5 - \Delta t$	$\delta\Delta t_5$ cosine β_5	$\delta\Delta t_5$ sine β_5
									$X = \Sigma\, \delta\Delta t_i$ Cosine β_i	$Y = \Sigma\, \delta\Delta t_i$ Sine β_i

tan $\alpha = Y/X$

$R = \sqrt{(X^2 + Y^2)}$

$\delta t_0 = t'_0 - t_0$

where α = bending plane angle
R = ultrasonic bending parameter
δt_0 = ultrasonic stretch