ACOUSTOELASTIC AXIAL STRESS MEASUREMENT OF SHORT BOLTS WITH LONGITUDINAL AND TRANSVERSE WAVES

Hajime Yasui
Instrument Engineering Department
Toyota Motor Co., Toyota 471-8571

Hirokazu Tanaka, Ikuya Fujii and Koichiro Kawashima
Department of Mechanical Engineering
Nagoya Institute of Technology, Nagoya 466-8555

INTRODUCTION

The bolts used for automobiles are relatively small compared with those used in power plants, steel bridges and frames. The precise control of the fastening force is required for important parts. The force measurement by torque wrenches is, however, unreliable because it does measure the frictional torque caused by the axial force not but axial force itself. Therefore direct measurement of the axial force in those bolts is required. The conventional ultrasonic bolt gages are not applicable for these short bolts because the bolt length uniformly stressed is small compared with the total length. An ultrasonic resonance method [1] is useful for axial stress measurement of these bolts, however, it requires long measurement time because of frequency sweep and both measurements in stressed and unstressed states.

In addition to the conventional axial stress measurement with longitudinal wave, the use of the velocity ratio of longitudinal and transverse waves have been proposed by Johnson, Holt and Cunningham [2]. However, the time resolution in their sing-around system was rather low thus the estimated stress by their method did not agree well with the measured.

The spread of high-speed digital signal acquisition and signal processing systems enables us to measure accurately and easily the time-of-flight (TOF) of ultrasonic pulses which propagates between the bolt head and end. In the present paper, an attempt is made to estimate accurately the axial stress in short bolts used for automobile with the velocity ratio method, digital pulse-echo method and FEM calculation.

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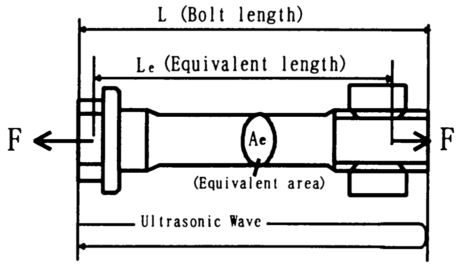


$$\beta = \frac{L}{L_e}$$

Figure 1. Model of axially stressed bolts. Definition of fraction of uniformly stressed length.

MODELLING

For a short bolt subjected to an axial force, there are some length partially stressed or unstressed. To take account this fact, we assume that the total bolt length L is composed of the uniformly stressed part Le and unstressed part L-Le, as shown in Fig.1. The former is subjected to an uniform tensile stress equals to σ =F/Ae, where F is the axial stress and Ae is the effective cross-sectional area. The ratio of β =Le/L is defined as "the fraction of uniformly stressed length", which depends on bolt geometry, axial force level and fastening condition.

For the uniformly stressed length, the longitudinal and transverse wave velocities depend on σ by the acoustoelastic law

$$V_L = V_{L0}(1+H_L\sigma), V_T = V_{T0}(1+H_T\sigma) \tag{1}$$

Where V_{L0} and V_{T0} are the longitudinal and transverse wave velocities in the unstressed state, and H_L and H_T are acoustoelastic coefficients of longitudinal and transverse waves.

Due to the axial stress, the bolt length increases by σ Le/E, therefore, the TOF of longitudinal and transverse waves for the whole length is given by

$$t_L = \frac{L}{V_{L0}}(1+H_L\sigma), t_T = \frac{L}{V_{T0}}(1+H_T\sigma) \tag{2}$$

Their ratio is expressed by

$$\frac{t_T}{t_L} = \frac{V_L}{V_T} = \left(\frac{V_{T0}}{V_{L0}}\right)[1+\beta(H_L - H_T)\sigma] \tag{3}$$

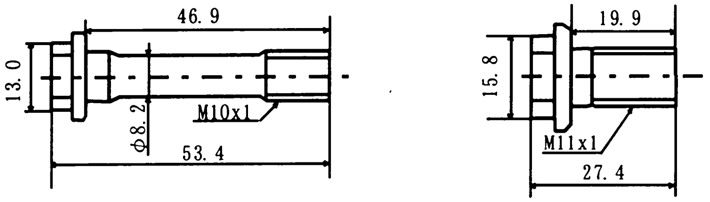
EXPERIMENTAL PROCEDURE

The geometry of the tested bolts is shown in Fig.2. The length of a fastened part is about 35mm for bolt (A) and 10mm for bolt (B). The both faces of the bolt head and end were finished by a grinder to be flat and parallel. The tensile strength, yield stress and the Young modulus of the bolt's material SCM440 are 1.1GPa, 1.0GPa and 210GPa, respectively.

The axial tensile force was applied for these bolts by using the fixture shown in Fig.3, to which axial compression was applied with a material testing machine.The echo signal from the bolt end was acquired by the digital ultrasonic system shown in Fig.4. The contact transducers of a 6.3mm diameter were attached on the bolt head: nominal frequency of 15MHz and 5MHz for longitudinal and transverse waves. The TOF was determined by the cross correlation method on the received waveforms which were accumulated 256 times. Also a combined L/T transducer (Panametrics X1040) was used to receive simultaneously the longitudinal and transverse waveforms. The extension of the bolts between the bolt head and end was sensed by a laser displacement sensor of which resolution is 0.5μm during the TOF measurement.

EXPERIMENTAL RESULTS

The ultrasonic measurements were performed for five bolts of the type (A) and (B). Figure 5 shows the received waveforms of the bolt (A) for longitudinal and transverse waves. The TOF of the bolt (A) between the first and second echoes are shown in Figs.6 and 7 for longitudinal and transverse wave. In addition, the axial elongation of the bolt (A) is shown in Fig.8. In Figs.(6)-(8), each mark denotes the measured result on a particular bolt among the five bolts. The width of the scattering band of the TOF and extension of five bolts are about 0.3%, which is



(A)

(B)

Figure 2. Geometry of bolt length in mm.

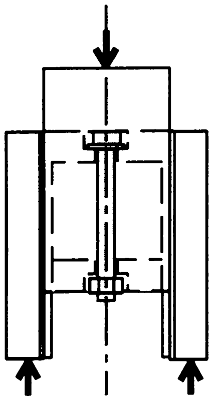


Figure 3. Fixture for tension test.

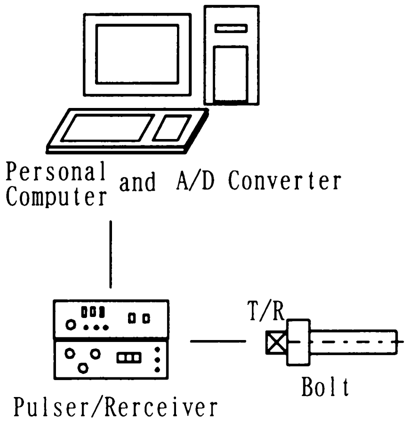


Figure 4. Digital ultrasonic measurement system.

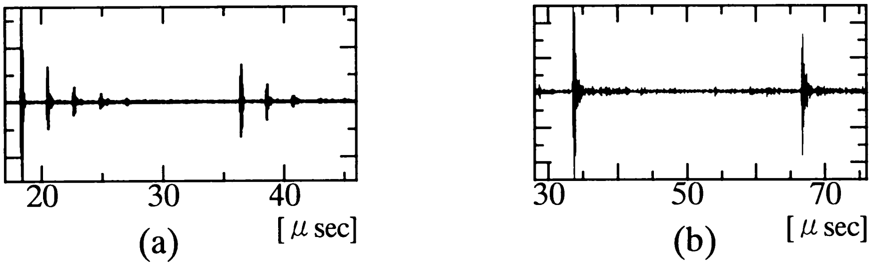


Figure 5. Received waveforms of bolt (A): (a) longitudinal wave, (b) transverse wave.

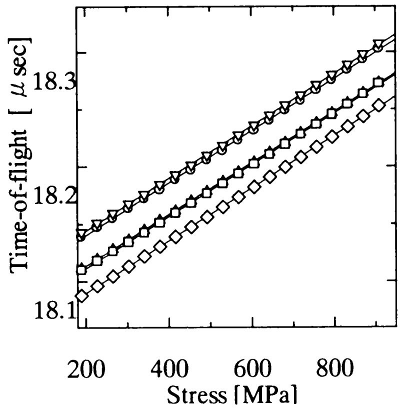


Figure 6. Change in time-of-flight of longitudinal wave (bolt A).

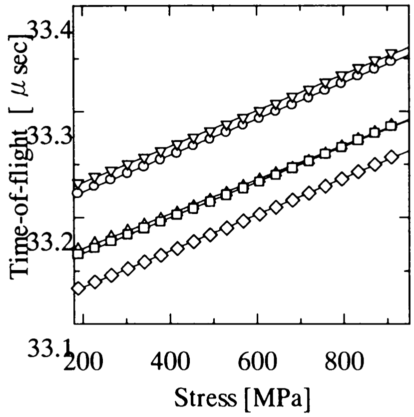


Figure 7. Change in time-of-flight transverse wave (bolt A).

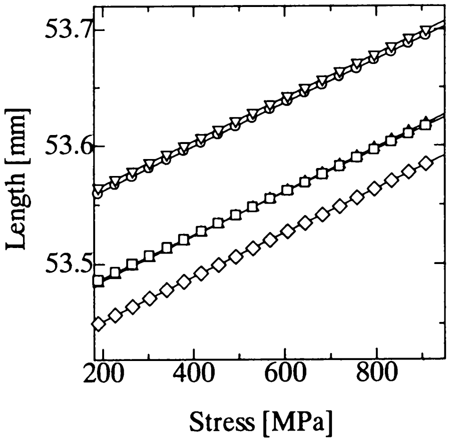


Figure 8. Axial extension of bolts stress (bolt A).

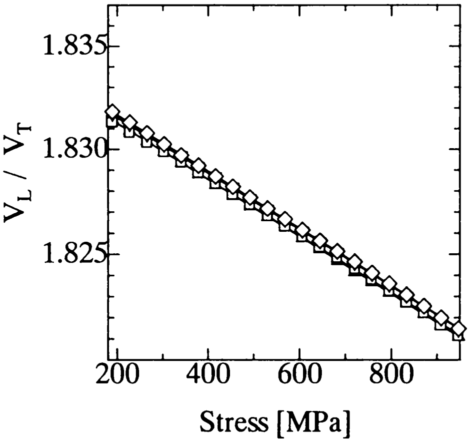


Figure 9. Change in velocity ratio vs. stress (bolt A).

much greater than the acoustoelastic effect. Their deviation pattern is similar, namely it depends on the slight difference in their initial length and misalignment. The scattering of their slopes with respect to stress is less than 3% except for one result on TOF of the transverse wave. This scattering of the slope may result from slight difference of fastening condition.

To eliminate the scattering of these results due to the difference of the initial length, the ratio of TOF of transverse wave to that of longitudinal one, namely the ratio of V_L/V_T is plotted in Fig.9. The width of the scattering band is reduced to less than 0.05% and that of their slope is about 1%. If these calibration lines are established, we can estimate the axial stress within 25MPa with the measured ratio of V_L/V_T. Of cause this method does not require the measurement of the TOF in unstressed state.

DISCUSSION

In real axial stress measurement of bolts, we could not make calibration tests, just shown in the previous sections, for all types of bolts, therefore, we have to construct the calibration lines shown in Fig.9 with the known geometry, mechanical and acoustoelastic properties of bolts and the size to be fastened. In the following, the procedure is given for the estimation of the acoustoelastic coefficients and "the fraction of uniformly stressed length".

The acoustoelastic coefficients of the bolt material are estimated by the results shown in Figs. (6)-(8), after the correction of the temperature dependence of the ultrasonic velocities if this is necessary. For a certain stress range, $\Delta\sigma$, shown in Fig.(8), the corresponding bolt elongation is found, from which the fraction of uniformly stressed length β is calculated. The strain increment for the stress range is also calculated by $\Delta\varepsilon = \Delta\sigma / E$. The change in the TOF of longitudinal or transverse wave for $\Delta\sigma$ is found from Fig.(6) or (7). The ratio to the TOF in the unstressed state are shown in Table 1 with the values mentioned above. Using Eqs.(1) and (2) as well as those values shown in the table, the acoustoelastic coefficients are calculated as shown in Table 2. It should be noted that the TOF measured is for the whole bolt length, while the change in the TOF results from the

Table I. Bolt extension, fraction of uniformly stressed length, strain and time-of-flight.

Type	Length (mm)	Stress Range (MPa)	Extension (mm)	Strain $X10^{-3}$	β	Δt_L (μ s)	Δt_T (μ s)	$\Delta t_L/t_L$ $X10^{-3}$	$\Delta t_T/t_T$ $X10^{-3}$
A	53.4	740	0.142	3.52	0.756	0.174	0.128	9.57	3.85
B	27.4	600	0.051	2.86	0.656	0.063	0.040	6.74	2.34

Table II. Acoustoelastic coefficients and gradient of t_T/t_L to stress.

Type	H_L	H_T	$\beta(H_L - H_T)$	Measured
A	$-12.4x10^{-6}$/MPa	$-2.1x10^{-6}$/Mpa	$-7.7x10^{-6}$/MPa	$-7.6x10^{-6}$/MPa
B	-12.4	-1.1	-7.4	-6.8

uniformly stressed length. The acoustoelastic coefficient of the longitudinal wave, H_L, is the same for the bolt (A) and (B), while that of the transverse wave, H_T, differs largely for two kinds of bolts. The acoustoelastic coefficient of the velocity ratio, V_L/V_T, is however, similar for both types of bolts. The value in the far right column shows the slope found from Fig.(9). The measured slope of the bolt (A) is very close to the estimated with the acoustoelastic coefficients, while that of the bolt (B) deviates by 8% from the estimation. This may result mainly from the deviation of the assumption of the model, namely, as shown in Fig.10, the bolt (A) has a certain uniformly stressed length, however, the bolt (B) has hardly any uniformly stressed region.

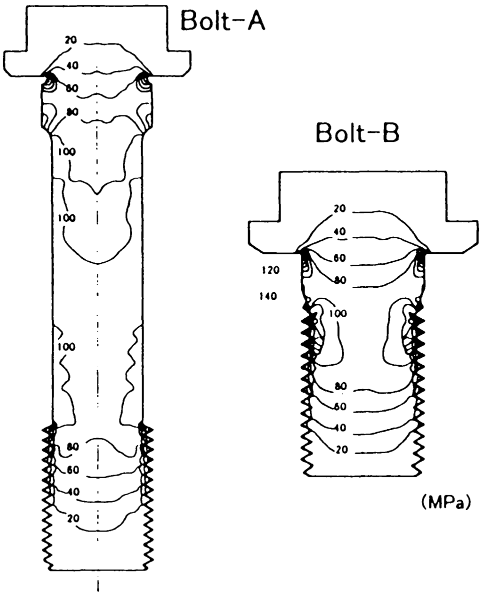


Figure 10. Axial stress distribution obtained by FEM analyses:(a) bolt A, (b) bolt B.

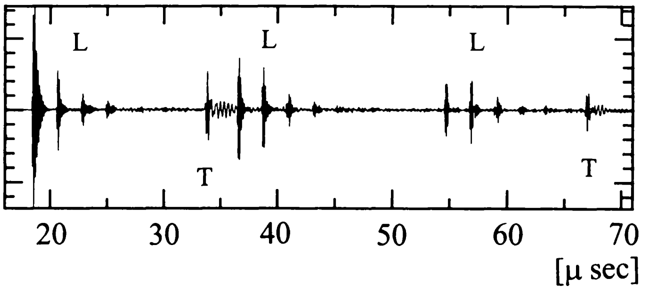


Figure 11. Received waveforms of bolt (A) with combined L/T transducer.
(L : 10MHz, T : 5MHz)

The remaining issue is to estimate "the fraction of uniformly stressed length." For a given geometry of a bolt and a part to be fastened, we can calculate the stress distribution within the bolt by finite element method, as shown in Fig.10. Based on these stress distribution, we can estimate the uniformly stressed length by weighted integration. For example, the length uniformly stressed for bolt (A) or (B) is estimated to be 39mm or 15mm from Fig.(10). The corresponding fraction of uniformly stressed length is 0.73 or 0.55 for the bolt (A) or (B). The former is close to the measured value in Table 1, however, the latter is smaller than the measured by 10%. For short bolt such as (B), it may be necessary to take account of shear stress distribution around the bolt head.

When we use a combined L/T transducer, we can measure the TOFs of the longitudinal and transverse waves by single measurement. The received waveforms with such a transducer are shown in Fig.11, where we can identify clearly the longitudinal and transverse wave signals. By setting appropriate gated windows, we can calculate their TOFs by the cross correlation method. Of cause, a special care should be paid for the control of the couplant thickness.

CONCLUSION

Acoustoelastic stress measurement of short bolts used for automobiles has established with a digital signal acquisition and signal processing system. The use of the TOF's ratio of transverse wave to longitudinal one eliminates the measurement in unstressed state. Moreover it gives precise estimation of the axial stress. The estimation of the bolt length uniformly stressed by FEM is effective for a long bolt of a length 53mm, however, it is inaccurate for a short bolt of 27mm where the axial stress distribution is complicated. Further modeling is required for very short bolts.

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