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Evaluation of Error of Acoustic Method and its Verification by Comparative Field Tests

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SUMMARY

In the practical application of acoustic method of discharge measurement, some problems, such as the protrusion of the transducer into the conduit and the incorrect alignment of the transducers, should be considered. In this paper, provisions for acoustic method in Japanese field efficiency test code (JEC-4002) to reduce the influence of above mentioned problems and their theoretical background based on the study by using numerical simulation for the velocity distributions along the acoustic paths between acoustic transducers were presented. Finally, two examples of the application of this method for the field efficiency test were presented.

RÉSUMÉ

Lorsqu'on utilise la méthode acoustique de la mesure du débit, il faut tenir compte de l'éventualité de problèmes tels que la protrusion du capteur dans le conduit, et le mauvais alignement des capteurs. Ce rapport présente les dispositions concernant la méthode acoustique spécifiées dans les normes japonaises relatives aux essais de rendement sur place (JEC-4002) afin de réduire l'influence résultant de tels problèmes, et leur arrière-plan en se basant sur l'étude effectuée au moyen de la simulation numérique pour la répartition des vitesses le long des routes acoustiques entre les capteurs acoustiques. Enfin, nous présentons deux exemples d'application de cette méthode pour les essais de rendement sur place.

1. Introduction

Recently, acoustic method of discharge measurement is being increasingly used in the field efficiency test of water turbines. Therefore, it is accepted in the field efficiency test code of IEC standard[1] and ASME standard[2]. However, in practical application of the acoustic method, some problems, such as the protrusion of the transducer into the conduit and the installation error arise[3]. Though these problems have not been considered in the above-mentioned standards, field efficiency test code of the Japanese Electrotechnical Committee, JEC-4002-1992, prescribes the treatments for these problems.

In the installation of the acoustic transducers for the acoustic method, the transducers usually protrude into the conduit to receive and transmit acoustic pulses. When such protruding transducers are used, the velocity distribution along the acoustic path from the inner wall of the conduit to the face of the protruding transducer is disregarded. Therefore, mean velocities measured by the acoustic method are always larger than the real mean velocities averaged over the whole acoustic path from wall to wall.

Based on the principle of the acoustic method, the locations of the acoustic transducers on the conduit are prescribed by the integration method. However, in practical application, it is very difficult to install the transducers on the exact locations as prescribed by the integration method. Therefore, the effect of the incorrect installation and the permissible limits for installation error from the exact location should be assessed.

For these reasons, Japanese field efficiency test code, JEC-4002-1992, prescribes the correction method for the protrusion of the transducer and allowance of the incorrect installation of the transducers. In this paper, the theoretical background for these provisions of JEC are show by using numerical simulations. Finally, the results of two comparative field tests are presented as examples of the application of JEC's provision for the acoustic method.

2. Japanese field efficiency test code for acoustic method

2.1 Japanese field efficiency test code, JEC-4002-1992

The Japanese electrotechnical committee revised the old field efficiency test code in 1992. After many studies to revise the old field efficiency test code, new test code, JEC-4002-1992, has introduced different provisions for acoustic method from IEC 41-1991, based on the study by using numerical simulation[3].

Main different points of JEC-4002-1992 are itemized below and the comparison with IEC 41 1991 is summarized in Table 1.

Table 1. The comparison with IEC 41 and JEC-4002

	IEC 41 1991	JEC-4002-1992
Necessary straight pipe for upstream and downstream of the measuring section	[Upstream] 20 × D (one plane) 10 × D (two plane) [Downstream] 3 × D	[Upstream] 20 × D (one plane) 10 × D (two plane) [Downstream] 3 × D
Correction for the protrusion of the transducer	No provision	Correction method is provided.
Maximum acceptable protrusion of the transducer	No provision	Less than 5% of the diameter of the conduit
Permissible limits of the installation error of the transducer	No provision	Less than 0.5% of the diameter of the conduit

(1) Correction method to reduce the influence of the protrusion of the transducer is provided in JEC, as described in section 2.2.
(2) The large protrusion of the transducer still produces serious influence for the discharge measurement, even if the correction for the protrusion of the transducer is made. Therefore, maximum allowable protrusion of the transducer from the inner wall of the conduit is given in JEC, namely less than 5 % of the inner diameter of the conduit. Theoretical background for this was given by the numerical simulation as described in chapter 3.
(3) The permissible installation error of the transducers is given in JEC, to prevent the serious error, which may occur when the installation error of the transducers from the exact location becomes as large as 0.5%~1.0% of the inner diameter of the conduit. Theoretical background for this provision was also given in chapter 3.

2.2 Correction method to reduce the influence of the protrusion of the transducers in JEC

In JEC, following correction method is given to reduce the influence of the protrusion of the acoustic transducer. The layout of the acoustic transducers and the acoustic paths are shown in Fig.1. Definitions of the symbols are as bellows.

- L_{wi} : The distance from the conduit wall to the conduit wall along the acoustic path i
- L_i : The distance from the face of the protruding transducer to the face of the other transducer along the acoustic path i
- ΔL_{ci} : The distance from the conduit wall surface to the face of the protruding transducer along the acoustic path i
- θ_i : The angle of the acoustic path i relative to the axis of the conduit

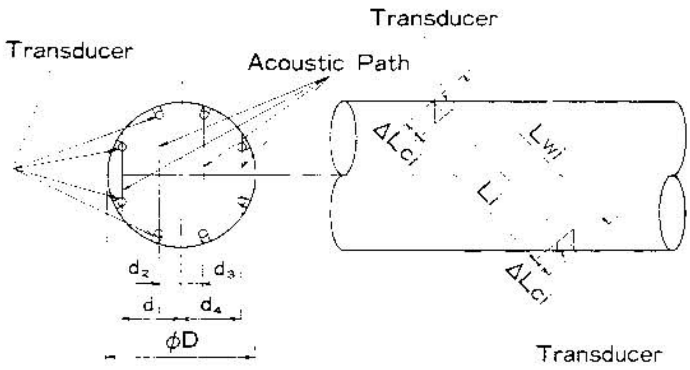

Fig.1 The layout of the transducers and the acoustic paths

Then, Fig.2 shows the velocity distribution along one of the acoustic path shown in Fig.1. Horizontal axis represents the distance L from the wall surface of the conduit along the acoustic path. Vertical axis means the axial velocity $u_i(L)$ along the acoustic path i.

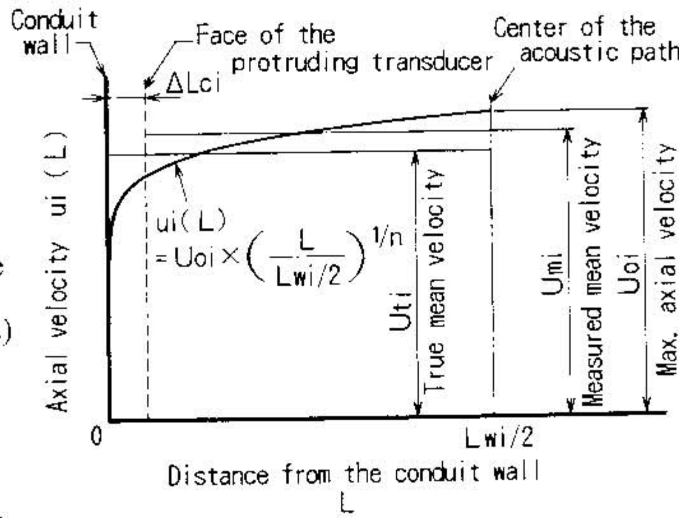

Fig.2 Velocity distribution along the acoustic path

Then, Uti defined as the true mean velocity along the acoustic path i and Umi defined as the measured mean velocity along the acoustic path i by the protruding transducers can be calculated as follows.

$$Uti = \frac{1}{Lwi/2} \int_0^{Lwi/2} ui(L)dL \qquad [2.1]$$

$$Umi = \frac{1}{Lwi/2 - \Delta Lci} \int_{\Delta Lci}^{Lwi/2} ui(L)dL \qquad [2.2]$$

If ui(L) is known, the influence of the protrusion of the transducer can be estimated. For this evaluation, it is assumed that the velocity distribution between the inner wall surface of the conduit along the acoustic path is represented by 1/n power law, as shown in Fig.2.

$$ui(L) = Uoi \times \left(\frac{L}{Lwi/2}\right)^{\frac{1}{n}} \qquad [2.3]$$

In Eq.[2.3], Uoi means maximum axial velocity along the acoustic path i. The exponent n should vary according to Reynolds number Re, as shown in Table 2. In actual site efficiency tests, the range of the Reynolds number is from 10^5 to 10^7, so the exponent n=10 may be used.

Table 2. Exponent of power law

Re	4.0×10^3	3.0×10^4	1.2×10^5	3.5×10^5	3.2×10^6	2.5×10^7
n	6	7	8	9	10	11

By using Eq.[2.3], Uti and Umi can be calculated as follows.

$$Uti = \frac{1}{Lwi/2}\int_0^{Lwi/2} ui(L)dL = \frac{n}{1+n} \times Uoi \qquad [2.4]$$

$$Umi = \frac{1}{Lwi/2-\Delta Lci}\int_{\Delta Lci}^{Lwi/2} ui(L)dL = \frac{1-\left(\frac{2\Delta Lci}{Lwi}\right)^{1+\frac{1}{n}}}{1-\frac{2\Delta Lci}{Lwi}} \times \frac{n}{1+n} \times Uoi \qquad [2.5]$$

From the comparison of Eq.[2.4] and Eq.[2.5], it can be seen that, if the velocity distribution is given by 1/n power law, the true mean velocity of the acoustic path Uti can be estimated from measured mean velocity Umi by the following equation. In this paper, the estimated true mean velocity is defined as the corrected mean velocity Uci as follows.

$$Uci = \frac{1-\frac{2\Delta Lci}{Lwi}}{1-\left(\frac{2\Delta Lci}{Lwi}\right)^{1+\frac{1}{n}}} \times Umi \qquad [2.6]$$

Then, true discharge can be estimated by using the corrected mean velocity Uci instead of the measured mean velocity Umi.

3. Numerical simulation to predict error of acoustic method

To estimate the influence of the protrusion of the transducers and the error caused by the incorrect installation of the transducers on the conduit, numerical simulation was carried out. Correction method for the protrusion of the transducers and the requirement for the installation accuracy of the transducers in JEC were theoretically determined, according to the following result of the numerical simulation.

3.1 Procedure of numerical simulation

For the numerical simulation, well-known equations of the velocity distributions of the turbulent flows in the closed conduit with smooth and rough inner wall, as shown in Table 3 and Fig.3, are used. The definitions of the symbols are shown in Table 3.

In the numerical simulation, the error of the acoustic discharge measurement is defined as the difference between the true discharge Qo calculated by the exact integration of the velocity distribution over the cross-section and the measured discharge Qm calculated by the mean velocities Umi along the acoustic paths. The mean velocity Umi is calculated by integrating the velocity along the acoustic path from the face of one transducer to the face of the other transducer in the opposite end of the acoustic path. Such simulation was conducted for various conditions, such as the protrusion of the transducer or the incorrect installation of the transducers. Then, the measured discharge Qm is calculated by a weighted average of these mean velocities Umi in the same manner as adopted in the actual acoustic discharge measurement as shown below.

$$Qm = K \times \frac{D^2}{2} \times \sum_{i=1}^{4} Wi \times Umi \qquad [3.1]$$

Where,
- K : The shape factor prescribed by the integration method
- D : The inner diameter of the conduit
- Wi : The weighting coefficient for the acoustic path i prescribed by the integration method

Table 3. Velocity distributions used in the numerical simulation

	Case	
for the conduit with smooth inner wall	1	n=6
	2	n=6.6
$\frac{u}{U_0} = \left(\frac{Y}{D/2}\right)^{\frac{1}{n}}$	3	n=7
	4	n=8.8
	5	n=10
	6	n=12
for the conduit with rough inner wall	7	$Ke/D=10^{-3}$
$\frac{u}{u_*} = 5.75\log\frac{Y}{Ke} + 8.5$	8	$Ke/D=10^{-4}$
	9	$Ke/D=10^{-5}$
	10	$Ke/D=10^{-6}$

where,
- u : The axial velocity in the cross-section
- U_0 : The maximum velocity in the cross-section
- Y : Radial distance from the inner wall of the conduit
- D : Inner diameter of the conduit
- u_* : The friction velocity
- Ke : Roughness of the inner wall of the conduit

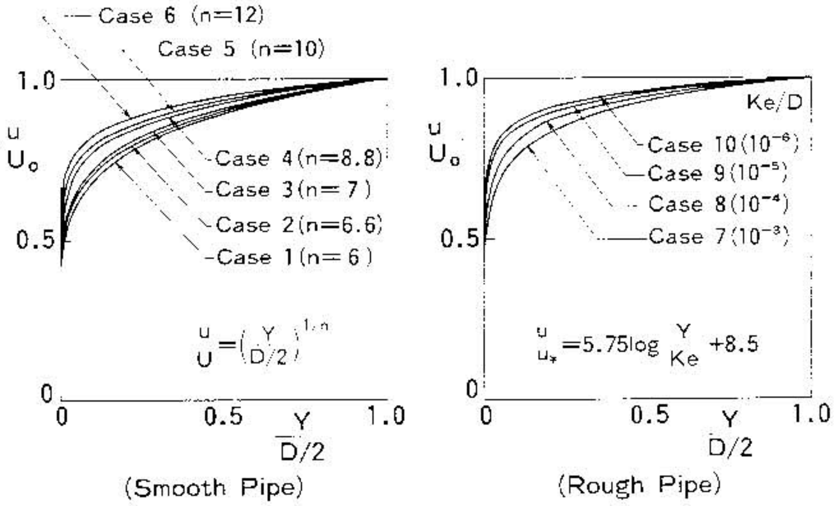

Fig.3 Velocity distributions in the conduit used in the numerical simulation

Table 4. The location of the acoustic path and coefficients of integration method for circular cross-section

	Gauss-Legendre		Gauss-Jacobi	
	Path 1 and 4	Path 2 and 3	Path 1 and 4	Path 2 and 3
$\frac{di}{D/2}$	±0.861136	±0.339981	±0.809017	±0.309017
Wi	0.176841	0.613298	0.217079	0.568320
K	0.994		1.000	

On the other hand, if the correction method of JEC is applied, corrected discharge Qc can be calculated by using Uci calculated by Eq.[2.6] instead of Umi, as shown below.

$$Qc = K \times \frac{D^2}{2} \times \sum_{i=1}^{4} Wi \times Uci \qquad [3.2]$$

The location of the acoustic paths, the weighting coefficient Wi and the shape factor K in the above equations are prescribed depending on the adopted integration method, such as Gauss-Legendre method or Gauss-Jacobi method, as shown in Table 4. The simulation study was done for the Gauss-Jacobi's method, since the acoustic flow meter systems adopting Gauss-Jacobi's method are more common in the market than those adopting Gauss-Legendre's method.

3.2 Influence of the protrusion of the transducers

Results of numerical simulation are shown in Fig.4 and Fig.5. Fig.4 shows the results without the correction for the protrusion of the transducer and Fig.5 shows the results with the correction for the protrusion of the transducer prescribed in JEC.

In these figures, Uo means the maximum axial velocity in the cross-section of the conduit and Ur means the reference velocity of the conduit, which is calculated by dividing the true discharge Qo by the sectional area of the conduit. Therefore, the ratio Uo/Ur shows the sharpness of the velocity distribution. Δd means the radial distance, on which the velocity cannot be measured due to the protrusion of the transducers. Referring to Fig.1, it can be seen that Δd is equal to ΔLci×sin θ i. In the numerical simulation, the ratio Δd/D varies from 0.0025 to 0.06.

According to the results shown in Fig.4, serious influence by the protrusion of the transducer is recognized when the ratio of Δd/D is larger.

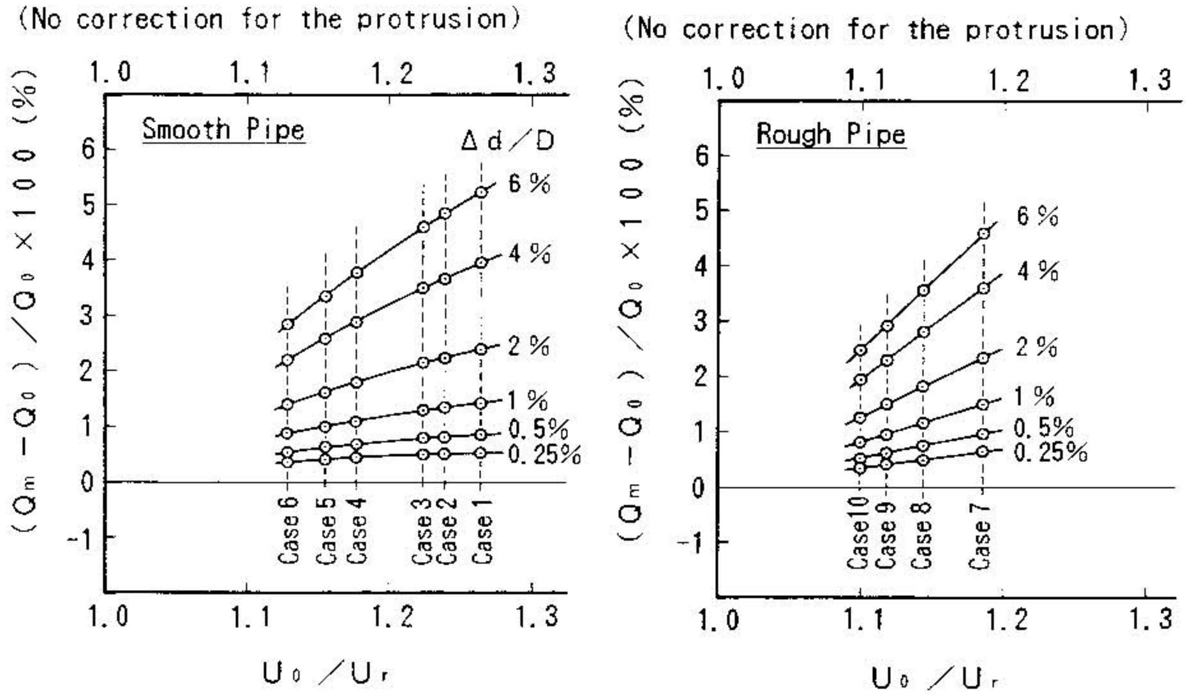

Fig.4 The results of the numerical simulation for the acoustic discharge measurement without the correction for the protrusion of the transducer

Results of the numerical simulation using the corrected discharge Qc instead of the measured discharge Qm are shown in Fig.5. In this case, exponent n=10 was adopted. It is known from these figures that, even if the correction method is applied, residual error may reach 0.2%~0.7%

in the range of Uo/Ur around 1.15 to 1.20, which corresponds to the ordinary turbulent flow. However, by comparing Fig.4 and Fig.5, it can be said that the influence of the protrusion of the transducer can be reduced considerably by the application of the correction method of JEC.

Therefore, it is necessary to apply this correct method prescribed in JEC, when the acoustic method with the protruding transducers is used.

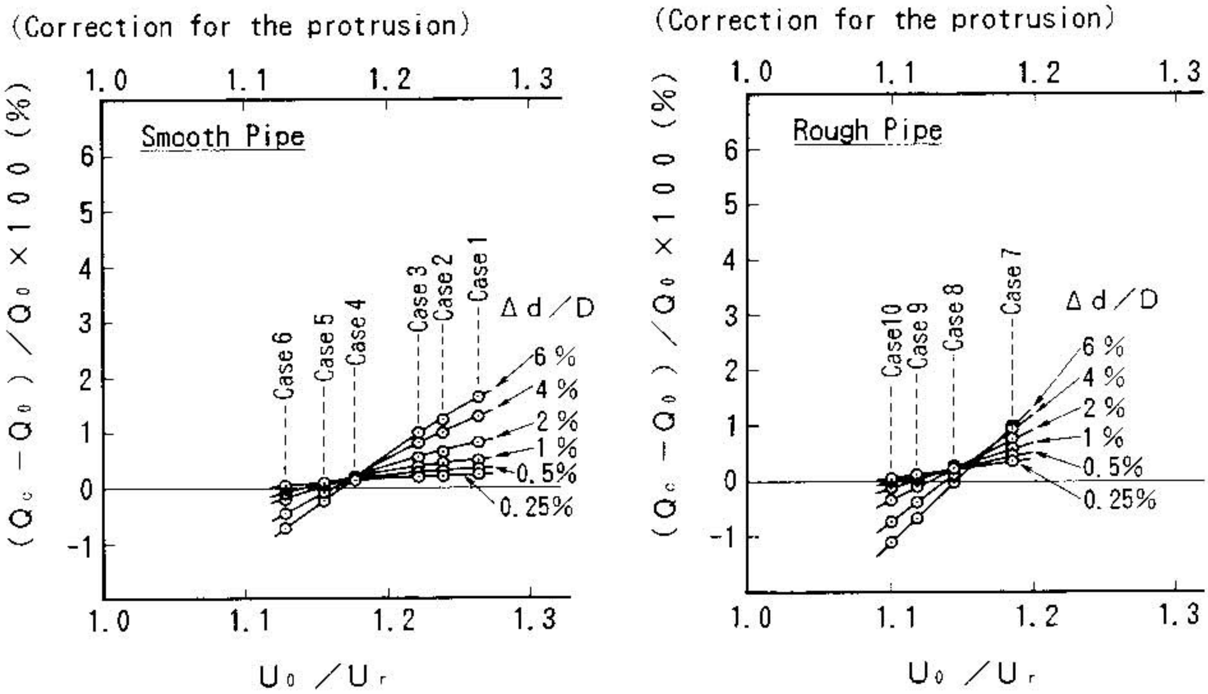

Fig.5 The results of the numerical simulation for the acoustic discharge measurement with the correction for the protrusion of the transducer

3.3 Error caused by the incorrect installation of the transducers

To estimate the effect of the incorrect installation and to discuss the allowable limits, the numerical simulation was conducted under the assumption shown in Fig.6.

The cross-section of the conduit was supposed to be an exact circle with the diameter D, and the location of all acoustic paths were supposed to shift from the exact location shown in Table 4 by the distance ΔX along the radius of the conduit. The negative value of ΔX means the shift toward the center of the conduit and the positive value of ΔX means the shift toward the outer of the conduit. Three cases of the protrusion of the acoustic transducer, such as Δd/D=0, 0.005, 0.05 were discussed, and the correction for the protrusion of the transducer prescribed in JEC was applied for each case. Numerical simulation was carried out by using the same velocity distributions as shown in Table 3 and Gauss-Jacobi's integration method.

In the numerical simulation, the discharge Qm is calculated so as to be measured by the real acoustic flow meter with the incorrectly installed transducers.

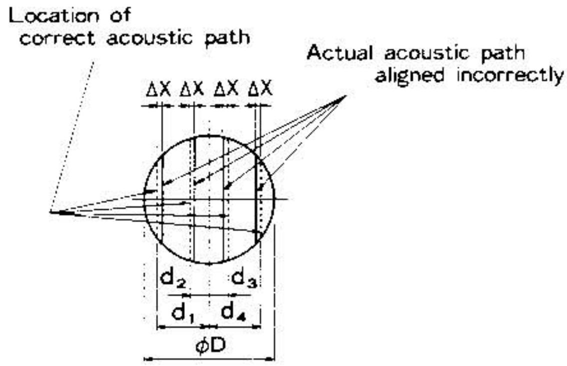

Fig.6 The layout of the acoustic paths with the incorrect installation of the transducers

Therefore, measured mean velocity Umi is calculated by integrating the velocity along the incorrectly installed acoustic path, and corrected velocity Uci is calculated by using eq.[2.6] with n=10. Then, corrected discharge Qc is calculated by using eq.[3.2].

The results of the numerical simulation are shown in Fig.7, Fig.8 and Fig.9. In these figures, the results for four cases of the velocity distributions, such as case 1, case 6, case7 and case10 in Table 3 are shown. In these figures, vertical axis shows the relative difference between the true discharge Qo and the corrected discharge Qc. Therefore, this value is affected by both the influence of the protrusion and incorrect installation. However, it can be said that increase of the difference between Qc and Qo due to the increase of ΔX/D shows the influence of the installation error of the transducers. From these results, following things can be seen.

(1) The effect of the installation error of the transducers is slightly influenced by the velocity distribution in the conduit and the protrusion of the transducer, but it is mainly influenced by the relative installation error ΔX /D.
(2) If ΔX/D varies by more than 0.005, the error increases or decreases seriously. Therefore, it can be said that the limit of allowance of the installation error of the transducers should be less than 0.5 % of the inner diameter of the conduit.

This is the theoretical background for the maximum allowance of the installation error of the transducers of JEC.

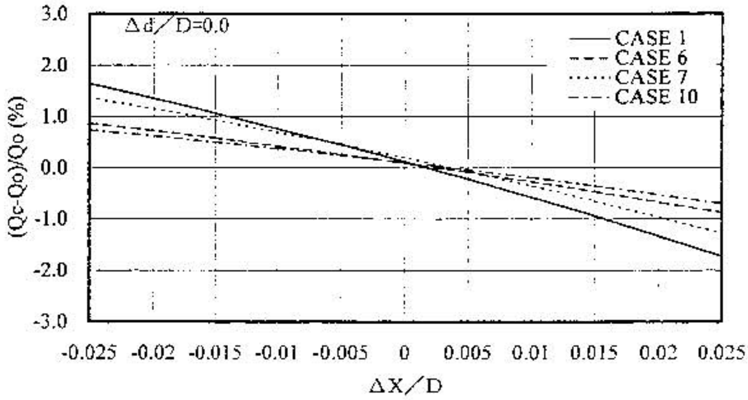

Fig.7 The results of the numerical simulation for the incorrect installation of the transducers (protrusion of the transducer Δd/D=0.0%)

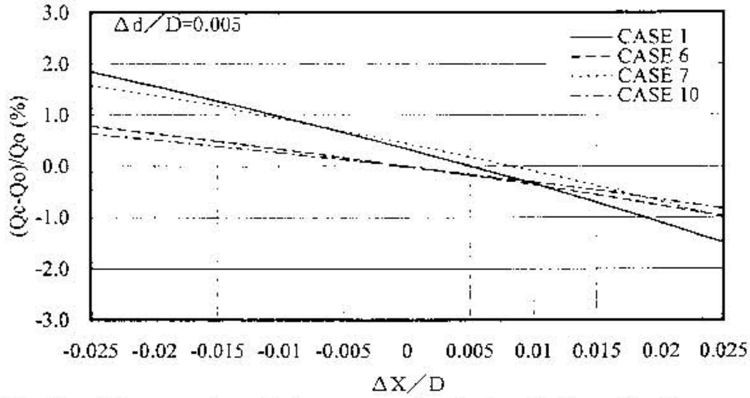

Fig.8 The results of the numerical simulation for the incorrect installation of the transducers (protrusion of the transducer Δd/D=0.5%)

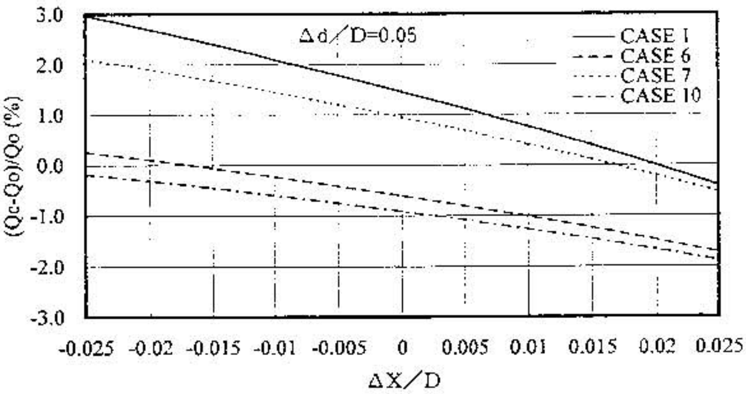

Fig.9 The results of the numerical simulation for the incorrect installation of the transducers (protrusion of the transducer Δd/D=5.0%)

4. Uncertainty of acoustic method in the practical application

A method to evaluate systematic uncertainty of acoustic method is given in JEC, which is set out below.

$$fq = \sqrt{fa^2 + fv^2 + fi^2 + fs^2} \qquad [4.1]$$

where,

fa : Uncertainty of the measurement of the sectional area of the conduit.
Usually, fa is calculated from ΔD, the uncertainty of the measurement of the diameter of the conduit, by the following equation.

$$fa = 2 \times \left(\Delta D / D \right) \qquad [4.2]$$

where,

ΔD : the uncertainty of the measurement of the diameter (D) of the conduit.

fv : Uncertainty of the measurement of the mean velocity along the acoustic path between the faces of the transducers

$$fv = \sqrt{\left(\Delta L / L \right)^2 + \left(\Delta\theta \times \tan\theta \right)^2 + 2\left(\Delta Dt / Dt \right)^2} \qquad [4.3]$$

where,

ΔL : Uncertainty of the measurement of the length (L) of the acoustic path between the faces of the transducers

$\Delta\theta$: Uncertainty of the measurements of the angle (θ) of the acoustic path

ΔDt : Uncertainty of the measurement of the difference between the traveling time (Dt) of the acoustic pulse

fi : Uncertainty of the integration of the velocity distribution, including the influence of the protrusion of the transducer, on condition that all transducers are installed at the exact locations prescribed in Table 4.

fs : Uncertainty caused by the incorrect installation of the transducers

In practical application of the acoustic method, each uncertainty can be calculated. Usually, it is relatively easy to measure diameter of the conduit and length and angle of the acoustic paths. Therefore, uncertainty of the dimension measurement is less than 0.2%. Then,

$\Delta D/D = 0.2\%$

$\Delta\theta \times \tan\theta = 0.2\%$

$\Delta L/L = 0.2\%$

In usual application, the difference of the traveling time between upstream direction and downstream direction Dt is considerably larger than the error of the time measurement. Therefore, uncertainty of time measurements can be disregarded. Then,

$\Delta Dt/Dt = 0$

From the results of numerical simulation in section 3.1, it can be seen that, even if the correction method is applied, residual error may reach 0.2%～0.7%. Therefore, uncertainty of the integration of the velocity distribution should be as follows.

fi =0.4%

From the results of numerical simulation in section 3.2, if maximum permissible installation error of the transducers is 0.5%, expected largest error for the calculated discharge is about 0.5%, Then,

fs =0.5%

Finally, total uncertainty of the acoustic method is

$$fq = \sqrt{(2 \times 0.2)^2 + 0.2^2 + 0.2^2 + 0.4^2 + 0.5^2} = 0.81\ \% \qquad [4.4]$$

The above mentioned uncertainty is calculated on condition that the correction for the protrusion of the transducer is carried out. Therefore, if the correction for the protrusion of the transducer is not carried out, large error more than 0.8% can be occur.

5. Result of site efficiency test

5.1 Test conditions and ratings of the tested turbine

Comparative flow measurements were conducted at two hydraulic power stations. Case A is the first case conducted at Okutadami power station in Japan, in which three 140 MW Francis type turbines were installed. Case B is the second case conducted at Sakuma Power Station in Japan, in which four 94 MW Francis type turbines were installed. The ratings of turbines in each power station were tabled in Table 5 and Table 6.

Table 5. The rated data of the tested turbine in Case A (Okutadami P.S.)

Net head H (m)	130.3
Discharge Qo (m^3/s)	69.3
Turbine Output Po (MW)	80.3

Table 6. The rated data of the tested turbine in Case B (Samuma P.S.)

Net head H (m)	105.0
Discharge Qo (m^3/s)	70.5
Turbine Output Po (MW)	66.5

In each case, flow measurements were conducted at one of those turbines, and the discharge measurement was performed by acoustic method with a single plane and four acoustic paths, and Model 7410 acoustic flow meter and Type 7600 acoustic transducers supplied by Accusonic Division, Ferranti O.R.E., Inc. were used. The acoustic transducers, which were used in these tests, protruded into the penstock from the inner wall, by 20.29 mm for those installed in the outer paths, and 18.79 mm for those installed in the inner paths. Pressure-time method was performed parallel to the acoustic method as a comparative flow measurement in both cases. The measuring section in the penstock, in which acoustic transducers were installed, is shown in Fig. 10 for Case A and in Fig.11 for Case B. The measuring sections in both cases had a circular cross-section and its inner diameter was 4051 mm for Case A and 4200 mm for Case B. These were measured values.

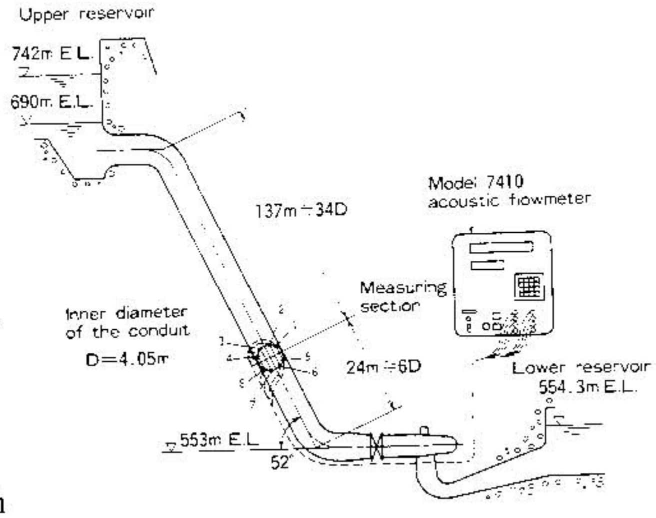

Fig.10 The layout of the pipeline and the measuring section of case A (Okutadami power station)

5.2 Test results and discussions

The test results were shown in Fig.12 and Fig.13. The measurements by the acoustic flow meter were carried out every two second during 300 seconds for each test point. Flow measurements by pressure-time method were carried out, just after the measurement by acoustic method had ended.

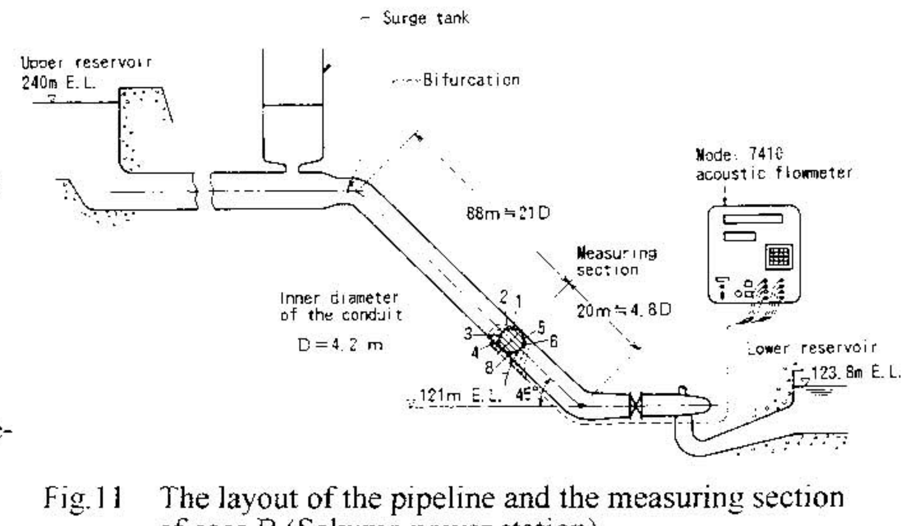

Fig.11 The layout of the pipeline and the measuring section of case B (Sakuma power station)

Fig.12 and Fig.13 show the comparison of the efficiencies obtained by three different method. One was pressure-time method, the second one was the acoustic method disregarding the influence of the protrusion of the transducer, and the third one was the acoustic method correcting the influence of the protrusion by the correction method of JEC. In these figures, η_0 is the maximum efficiency obtained by the acoustic method correcting the influence of the protrusion and P_0 is the turbine output tabled in Table 5 or Table 6. From these figures, It can be seen that the efficiency values measured by the acoustic method with and without the correction for the protrusion of the transducers were lower than those measured by the pressure-time method. However, these differences were decreased by the correction for the protrusion of the transducer by approximately 0.5 % both in case A and case B. Therefore, it can be said that the correction method prescribed in JEC can reduce the influence of the protrusion of the acoustic transducer.

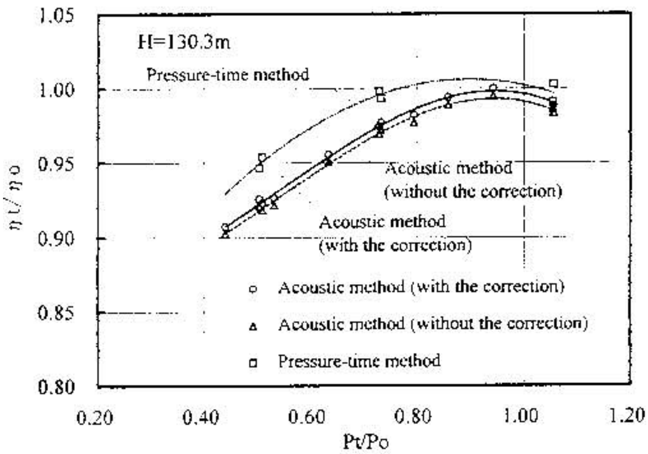

Fig.12 Results of the efficiency measurement for case A (Okutadami power station)

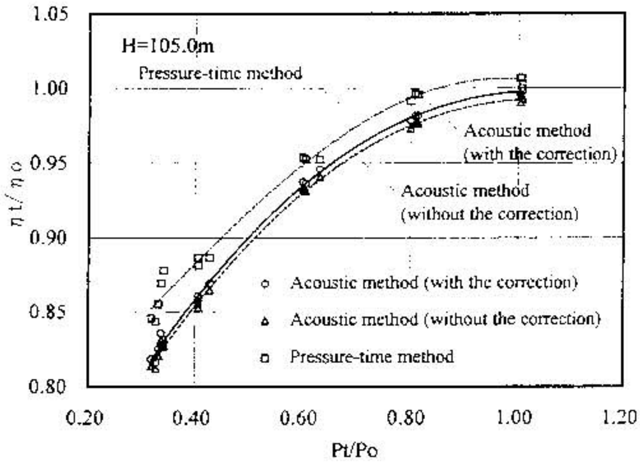

Fig.13 Results of the efficiency measurement for case B (Sakuma power station)

6. Conclusions

(1) Serious influence will be involved in the discharge measurement, if the protrusion of the transducers is large. A correction method as given in JEC is required to reduce the error.
(2) Correction method of JEC can reduce the influence of the protrusion of the transducers considerably. However, residual error as much as 0.2 %~0.7 % may remain for ordinary turbulent flow in the closed conduit.
(3) The installation error of the transducers corresponding to more than 0.5% of the inner diameter of the conduit will cause serious error as much as 0.5 % of the true discharge. Therefore, it is recommended that the installation error of the transducers should be less than 0.5%, as prescribed in JEC.
(4) From the results of comparable field efficiency test, the calculated efficiencies obtained by the correction method of JEC showed better agreement with the results of pressure-time method than those without the correction.

7. Reference

(1) IEC 41 1991, "Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines"
(2) ASME PTC 18-1992 "Hydraulic turbines"
(3) Sugishita,K., Motoki,T., Kosugi,T., "Correction method to improve the accuracy of multipath acoustic flowmeters", IAHR 1992, San Paulo, Brazil