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ROBUST POST-PROCESSING PROCEDURE FOR MULTI-HOLE DIRECTIONAL PROBES

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ABSTRACT

Aerodynamic probes have been extensively used in turbine performance measurements for over 60 years to provide flow direction and Mach numbers. In turbomachinery applications the absence of adequate optical access prevents the use of laser-Doppler-anemometry (LDA), laser-two-focus velocimetry, particle-image-velocimetry (PIV). Moreover, multi-hole pressure probes are more robust than hot-wire or hot-fiber probes, and less susceptible to gas contamination.

The pressure readings are converted into flow direction using calibration maps. Some researchers tried to model theoretically or numerically the calibration map to speed up the process. Due to manufacturing abnormalities, experimental calibration is still essential. The calibration map is obtained in a wind tunnel varying the yaw and pitch angles, while recording the hole-pressures. With the advent of powerful computers, researchers introduced sophisticated techniques to process the calibration data. Depending on the geometry or manufacturing imperfections a conventional calibration map is distorted, with multiple crossings resulting in the inability to identify a unique flow direction.

In the current paper, a new calibration and data processing procedure is introduced for multi-hole probe measurements. The new technique relies on a set of calibration data rather than a calibration map. The pressure readings from each hole are considered individually through a minimization algorithm. Hence, the new technique allows computing flow direction even when a hole is blocked during the test campaign. The new methodology is demonstrated in a five-hole probe including estimates on the uncertainty.

INTRODUCTION

Multi-hole probes are reasonably low cost and durable measurement techniques, readily applicable to turbomachinery environments. Multi-hole probes provide pitch and yaw flow angles together with total and static pressures. The inline holes provide either yaw or pitch angle information whereas holes in the normal planedefine true pitch or yaw.

The probe calibration is usually carried out in a closed wind tunnel [1] or a free jet [2] at multiple flow directions. The probe is rotated to vary the flow incidence. The pressure level of each hole is recorded while the probe is kept stationary [3]. Potential flow theory may be used to model the flow around the probe head [4], allowing to examine the map limitations and enhancing the calibration range. In case of supersonic flows, the calibration could be assisted by numerical simulations. For instance a three dimensional thin layer Navier-Stokes code was used to calibrate a conical head five-hole probe at Mach number from 1.75 to 2.75 [5].

The flow direction is generally expressed by a pressure difference between the probe holes. Then, the non-dimensional pressure differences are presented in calibration maps. Morrison et al. [6] give a detailed explanation of the calibration and data processing procedure using four non-dimensional parameters. Sumner [7] showed that both techniques provide similar accuracy when the flow incidence is below 30 deg. Baskaran et al. [8] and Rediniotis and Vijayagopal [9] proposed a technique using artificial neural-network to obtain directly the unknowns from the calibration map. Reichert and Wendt [10] used Taylor's series expansion to model the calibration maps.

Different techniques are used to processes the multi-hole probe measurements. In the majority of publications, pressure readings from all the holes are reduced to non-dimensional numbers that are then compared to the calibration maps using different approaches. Gallington [11] proposed a polynomial curve fitting method for the data reduction, a third order least-square fitting was employed between flow conditions and calibration coefficients. Similarly, Johansen et al. [12] used least-square curve fitting technique. Alternatively, a direct interpolation technique is introduced [13, 14, 15] for post-processing of the data.

The accuracy of the data processing technique can be improved applying different methods. Wenger and Devenport [16] utilized a two step data reduction technique in order to improve the accuracy of the Gallington's method. They performed a least-square surface fitting on a calibration data considering global data points. Then, a local interpolation was performed in order to improve the accuracy. The accuracy of the direct interpolation is increased when the calibration region is divided into several regions especially for seven-hole probes [17]. Pisasale and Ahmed [18] improved the direct-interpolation technique for an extreme flow angles up to ±75 degree by applying additional parameters for the range of extreme flow incidences. The definitions of the non-dimensional pressure parameters are modified in order to have a linear variation with flow angle [19]. This modification improves the interpolation accuracy in the calibration domain.

In the current paper, a new methodology that uses a database and a minimization routine is proposed. Each hole-pressure reading and their interaction is considered. Hence, the unique relationship between holes allows identifying the flow angle with high accuracy. The data reduction is still valid even when one of the holes gets clogged. This offers a big advantages compared to the existing tools.

NOMENCLATURE

cp	calibration coefficient
err	error
M	Mach number
p	Pressure [bar]
r	regression coefficient

Subscripts

0	Stagnation properties
1	upper hole of 5-hole probe
2	lateral hole of 5-hole probe
3	lower hole of 5-hole probe
4	lateral hole of 5-hole probe
5	central hole of 5-hole probe
ave	average
cal	calibration data
meas	measurement
s	static properties

DATA PROCESSING BASED ON CALIBRATION MAPS

Determination of the calibration probe coefficients

In a five-hole probe (Fig. 1) let us consider four unknowns, namely yaw angle, pitch angle, total and static pressure. In the traditional processing technique those unknowns are calculated by using non-dimensional parameters. The five pressure readings are reduced to four non-dimensional coefficient namely cp_v, cp_w, cp_5 and cp_{ave} Eq.s 1-2 [6] where "p_s" refers to the static pressure readings. The non-dimensional parameters are historically represented in calibration maps (Fig. 1), each couple of yaw and pitch angle are associated to a unique cp_v, cp_w, cp_5 and cp_{ave}. Because the relationship between coefficients varies slightly with speed, the calibration maps need to be provided at several flow speeds covering the range of application.

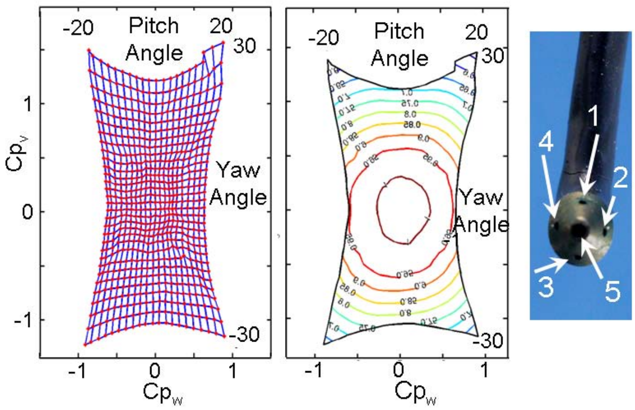

Fig. 1: Five-hole probe hole orientation (right), flow angle - cp_w,cp_v relation (left) cp_5 - cp_w,cp_v relation (middle).

$$cp_v = \frac{p_2 - p_4}{p_5 - p_{ave}} \qquad cp_w = \frac{p_3 - p_1}{p_5 - p_{ave}} \qquad \text{Eq. 1}$$

$$cp_5 = \frac{p_5 - p_s}{p_0 - p_s} \qquad cp_{ave} = \frac{p_{ave} - p_s}{p_0 - p_s} \qquad \text{Eq. 2}$$

Flow angle and Mach number evaluation

During a measurement data reduction, the non-dimensional coefficients (cp_w, cp_v, cp_5, cp_{ave}) are at each instant and location. Then, we make a guess on the flow Mach number for instance 0.2. The calibration maps cp_v, cp_w at M=0.2 are used to find angles and cp_5, cp_{ave}. Once cp_5, cp_{ave} evaluated M can be computed. By using cp_5 and cp_{ave}, the total pressure and static pressure are derived. Finally, the initially predicted Mach number is verified using Eq. 3. The procedure is restarted if the initial guess and the final Mach number do not match. The algorithm is summarized in Fig. 2.

$$M = \sqrt{\left(\left(\frac{p_s}{p_0}\right)^{\frac{1-\gamma}{\gamma}} - 1\right)\frac{2}{\gamma - 1}} \qquad \text{Eq. 3}$$

The traditional technique mostly fails when the map cells are much distorted or one of the pressure holes is clogged. The bilinear interpolation performed in a cell leads to large errors in distorted cells. On the other hand, the hole diameters are very small (<0.8 mm) in general to keep the probe size in an acceptable range. Hence, the pneumatic line can easily be blocked by particles during the operation. Such problem results in a wrong pressure reading; hence some of the non-dimensional parameters could not be calculated and the traditional 5-hole probe data reduction can not be carried out.

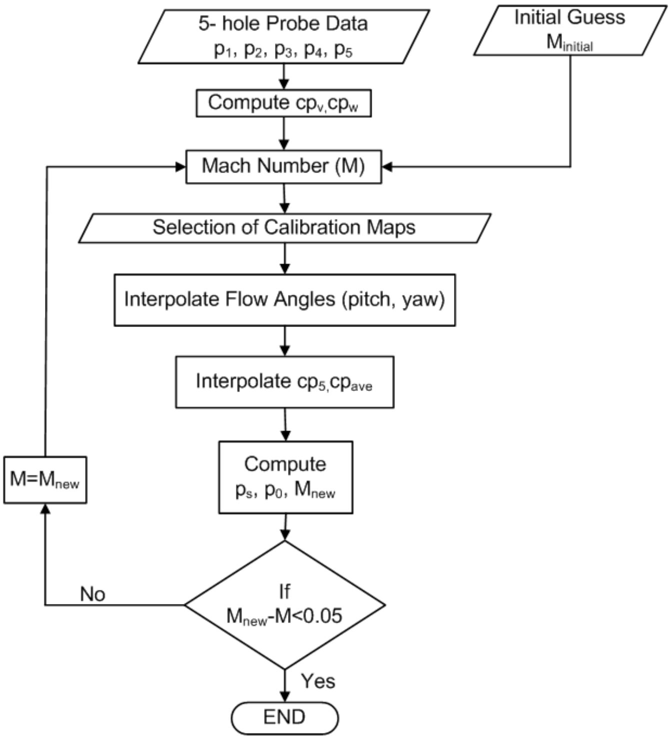

Fig. 2: Traditional data processing algorithm.

ROBUST MULTI-HOLE TECHNIQUE

Procedure based on a calibration database

A new processing procedure has been developed in order to increase the accuracy of the directional probe in cases where the traditional technique fails. The new technique works based on correlation between the measurements and calibration data of each individual hole. The pressure readings of the probe are expressed as six non-dimensional parameters namely, cp_1, cp_2, cp_3 cp_4 cp_5, cp_{ave}. (Eq. 4-6). P_0 is the measured total pressure. The lateral-hole readings were non-dimensionalized by the dynamic head. Those coefficients are recorded in a database together with the corresponding flow angles, total and static pressure values.

$$cp_1 = \frac{p_1 - p_s}{p_5 - p_s} \qquad cp_2 = \frac{p_2 - p_s}{p_5 - p_s} \qquad \text{Eq. 4}$$

$$cp_3 = \frac{p_3 - p_s}{p_5 - p_s} \qquad cp_4 = \frac{p_4 - p_s}{p_5 - p_s} \qquad \text{Eq. 5}$$

$$cp_5 = \frac{p_5 - p_s}{p_0 - p_s} \qquad cp_{ave} = \frac{mean(p_{1-4}) - p_s}{p_0 - p_s} \qquad \text{Eq. 6}$$

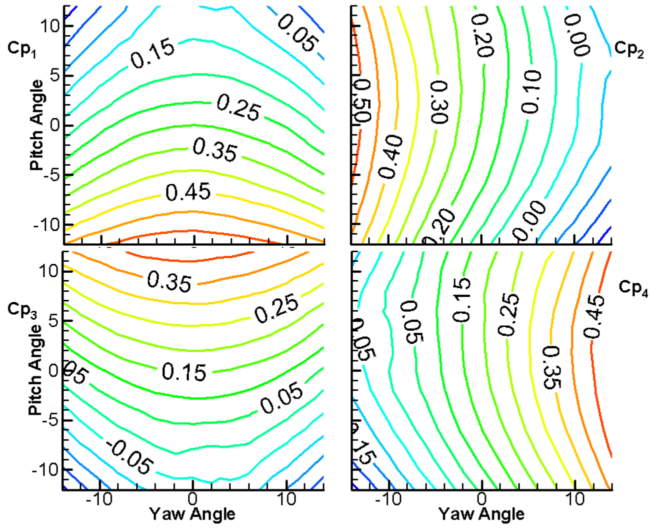

Fig. 3: Variation of non-dimensional parameters (cp_1, cp_2, cp_3, cp_4) with flow angle

There is no calibration map generated in this procedure. The non-dimensional pressure readings from each lateral hole are plotted in Fig. 3. The relationship between cp_1, cp_2, cp_3, and cp_4 at a given flow angle is unique [10] at constant flow speed. This means that for a known set of coefficient (cp_1, cp_2, cp_3, cp_4), only one angle combination exists. This unique relationship is used in the data post-processing. Once the measurements are performed, the coefficients are computed using an estimated static pressure value. The static pressure estimation is easily obtained by endwall pneumatic taps. Then, the computed coefficients as well as their interactions are compared with the corresponding values in the database. The quality of the comparison for each flow angle is defined by a linear regression coefficient as given in Eq. 7. When the probe readings are in good agreement with the calibration database values, the regression coefficient approaches unity. An example is given using the data taken by a five-hole probe. The probe is set at a yaw angle of 6 deg. and pitch angle of 0 deg. at the outlet of a free jet. The data is processed with the proposed technique. The regression coefficients (r^2) are computed using calibration database and distribution of ($1-r^2$) is plotted over the calibration range in Fig. 4. The results show that the regression coefficient increases around the actual value.

$$f = (cp_1^2, cp_2^2, cp_3^2, cp_4^2, cp_5^2, \overline{cp}_{1:5}^2, (cp_1 + cp_2)^2, (cp_1 + cp_3)^2, (cp_2 + cp_3)^2, (cp_2 + cp_4)^2, (cp_3 + cp_4)^2) \qquad \text{Eq. 7}$$

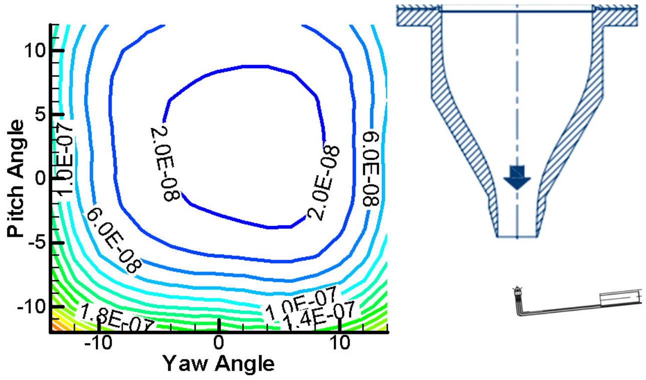

Fig. 4: Distribution of (1-r^2) for flow angle of 6 deg., 0 deg.

The computed regression coefficients later are used to find the flow angle by performing surface fitting. Polynomial fitting is performed in both directions as shown in Fig. 5. In order to increase the fitting accuracy only half of the results with highest regression coefficient are used. Additionally, the weight of the five points with highest regression coefficient is kept higher. Using the fit parameters the measured flow angles are obtained by finding the valley. The cp_5, and cp_{ave} coefficients are interpolated in the database using both flow angles in order to compute the total and the static pressure. The obtained static pressure value is compared with the initial guess. If the difference is lower than a certain threshold the calculation stops otherwise the procedure starts with the updated static pressure. The post-processing procedure is summarized in Fig. 6. the same procedure may be implemented for any multi-hole directional probe.

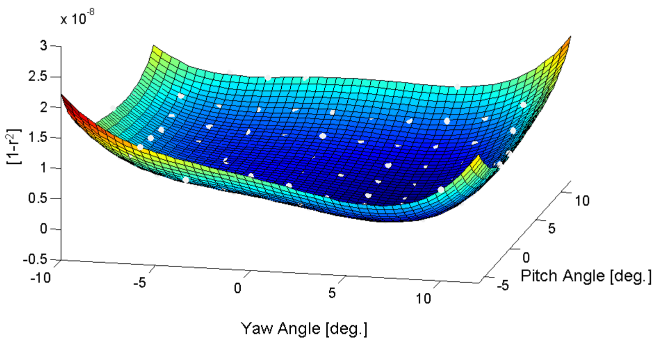

Fig. 5: Surface fit for flow angle of 6 deg., 0 deg.

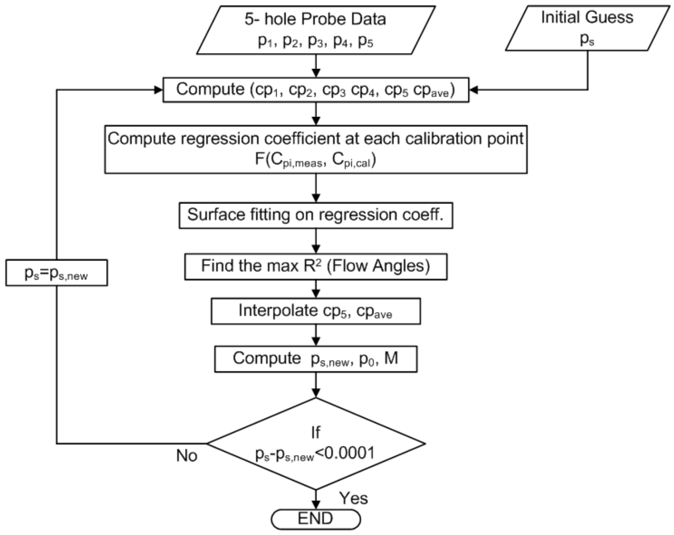

Fig. 6: New data processing algorithm

The new technique offers also big advantages in case of a failure of a pressure reading. Since the technique is based on the correlation, the correct flow angle is still captured, though; the accuracy of the technique is reduced. Consequently, this procedure is also applicable in case of local separation. This allows increasing the range of use multi-hole directional probes. This is of particular interest to multi-hole probes at high flow incidence due to the local flow separation.

Application to five-hole probe

A five-hole probe was calibrated in a free jet facility at Mach 0.17. Let us consider a set of 64 yaw and pitch angles combinations. For each of this point in the calibration data, the pressure data regarding that point is eliminated. The new robust procedure is used to evaluate the missing pressure data, the errors in flow angles will be evaluated.

The number of iteration for each flow angle is also fixed to five. Fig. 7 shows the convergent history for all positions. The difference in yaw and pitch angles and the regression coefficient of the surface fit are plotted. The results are converging rapidly after first iteration and remain unchanged after the third one. The regression coefficient for the surface fit is always higher than 0.997 and it is not significantly affected during the iteration process.

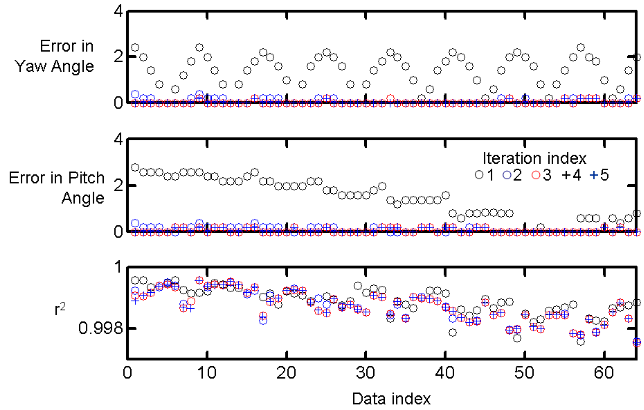

Fig. 7: Convergence history

The final error distribution in yaw and pitch angle is given in Fig. 8. The dots show the evaluated angular positions (true flow angle) whereas the counter plots show the difference between the computed angle by the method and the true flow angle. The methodology predicts very well the exact flow angle in general.

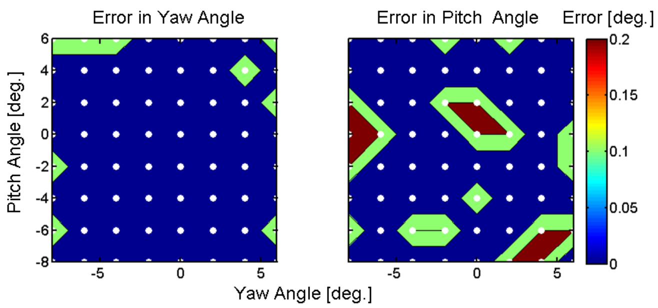

Fig. 8: Error evaluation in yaw and pitch angles

Demonstration of use of five-hole probe with a blocked hole

The traditional technique is partially used when a hole is blocked by particles like dust in the flow. In such case, the usage of the map is limited. However, the proposed technique has a potential to use the probe in such condition for full domain. In order to evaluate this one of the lateral hole is artificially blocked by considering the pressure value is equivalent to zero. All four holes are blocked one by one in order to check the dependencies.

Although only four-hole in use, variation of the regression coefficient over the database still gives a single valley as shown in Fig. 9. However, in contrast to the five-hole arrangement the valley is more smooth and wider.

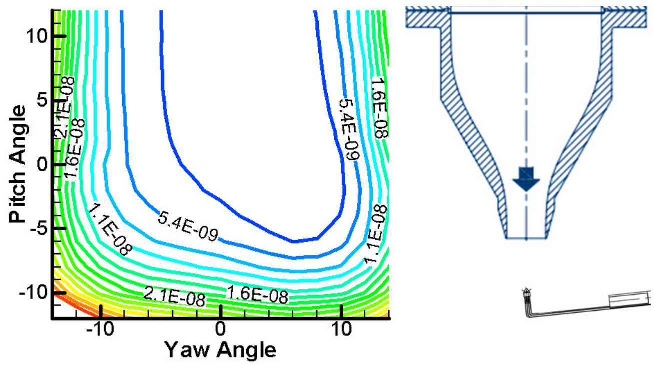

Fig. 9: Distribution of (1-r^2) for flow angle of 6 deg., 0 deg. with four-hole arrangement

The fitted surface is also depicted in Fig. 10. The fitted surface does not have a strong gradient at one of its corner due to the missing hole. Due to this wide valley, the accuracy of the methodology is slightly penalized.

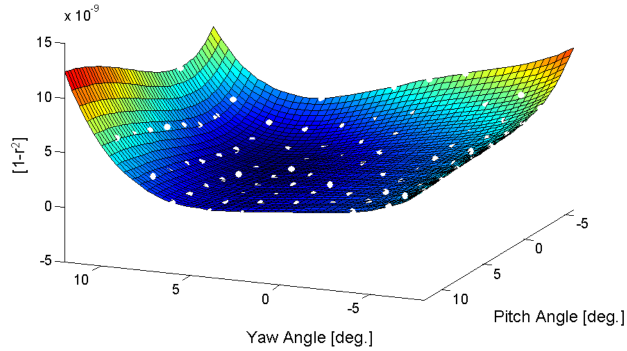

Fig. 10: Surface fit for flow angle of 6 deg., 0 deg. with four-hole arrangement

Figures 11 show the final error in yaw and pitch angle measurements for different blocked lateral holes. Similar to Fig. 8, the dots on the plots shows the real flow angle whereas the counter plot shows the difference between the real flow angle and the results of the new technique. The error kept lower than 1 deg. in general. The error increases when flow becomes aligned with the blocked hole. However it still remains in the acceptable range.

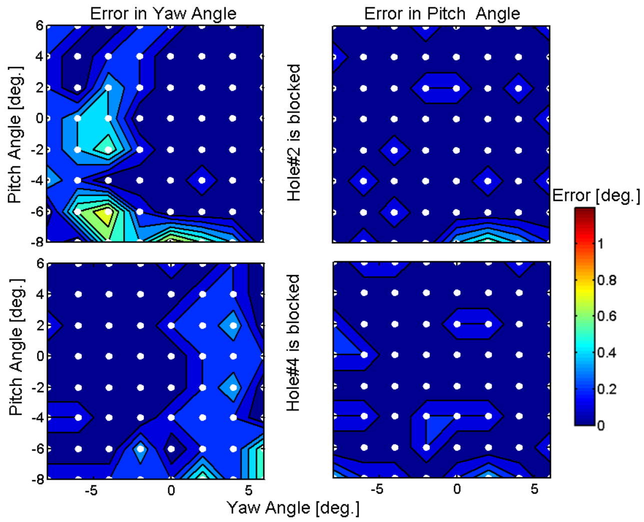

Fig. 11: Error in yaw and pitch angle when hole number 2 and 4 is blocked

CONCLUSIONS

A new robust post-processing procedure is proposed in the current paper. The technique considers pressure readings from each hole and their interactions as a parameter. Those parameters are used to build up a database during calibration process. Therefore, no calibration map required. During the post-processing, the measured data are compared with the data in the database which is represented as linear regression coefficient. The procedure allows finding the correct flow angle by finding minima on fitted regression coefficient. Therefore, the same technique can be applied to any multi-hole probe measurement without any change.

A validation case is run using the calibration data. The new methodology is able to provide the flow angle with a maximum error of 0.2 deg.

The new technique allows using the probe in case of lost of one of the lateral hole due to the blockage. This is the one of the major advantage of the technique compared to the conventional method.

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