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Fringe Correlation Method for Helicopter Rotor Blade Deflection Measurement

R.H.G. Müller *, K. Pengel +

* F.I.B.U.S. Research Institute, Paul-Klee-Weg 8, D-40489 Düsseldorf, Germany
+ DNW, Postbus 175, 8300 AD Emmeloord, The Netherlands

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Abstract

This paper presents the fringe correlation method (FCM) for 3-dimensional surface deflection measurement at high accuracy and resolution. Especially fast moving surfaces like helicopter rotor blades can be inspected. Set-up of the method is very simple, using a fringe projector that may be a powerful slide projector equipped with a black and transparent fringe slide, and a CCD video camera with a fast shutter triggered by the rotor at distinct azimuthal positions. Surface deflections will result in a displacement of the projected fringe image that can be detected by using an image analysis system. When comparing the images with a reference image, a very high resolution can be obtained by applying cross-correlation techniques with sub-pixel accuracy. It is possible to perform relative or absolute measurements. As an example some special rotor configurations with higher harmonic control (HHC) conditions are presented that have been investigated at the helicopter test rig ROTEST II of the German Air and Space Laboratory, DLR in the Large Low-Speed Facility (LLF) of the German Dutch Wind Tunnels (DNW). Results include the graphical display of blade surface deflection and angle of attack variations due to the influence of HHC.

Introduction

With introduction of new rotor control techniques like individual blade control (IBC) or higher harmonic control (HHC) the reduction of rotor noise and dynamic blade stress has become more promising than ever before. For any optimization of harmonic or non-harmonic control input at the blades, however, it is very important to have exact data of blade deflection and spanwise distribution of the angle of attack. This is especially important as the elastic rotor blades have relatively low frequency modes for flapping or torsion. A reasonable comparison with numerical simulations cannot be expected without an exact knowledge of the geometrical response of the blade on the control input.

Different approaches for collection of the deflection data have been developed in the past, including laser beam reflection measurement or observation of markers at the blade tip (Refs. 1, 2). Using those methods, only a few points on the blade surface can be determined at a time. For the elastic blade, however, it is strongly suggested to inspect the complete deflected surface.

Therefore, a new method for surface deflection measurement had been developed at the DNW (Ref. 3), the "Projected Grid Method" (PGM). This method is based on the detection of the displacement of fringes projected on the surface. The detection algorithm is a simple contour following method for binarized fringe images with a maximum resolution of one picture element (pixel) of the camera. As this was too low a resolution for accurate torsion measurement, the complete image had to be divided into several partial subimages with all the known problems of reconstruction and recombination. As the principle of the method, however, was very promising, an improved new version of image analysis software was developed at FIBUS research institute, the "Fringe Correlation Method" (FCM).

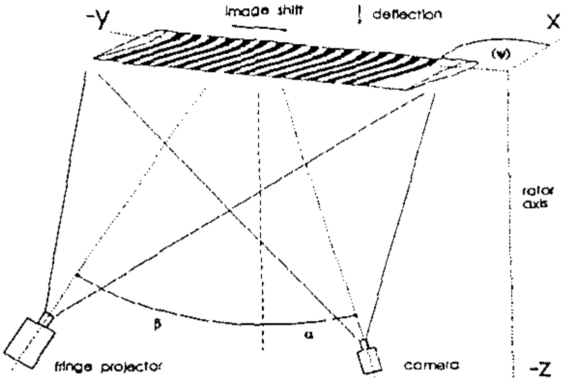
Another interesting method presented only few months ago is the Projected Moiré Interferometry method (PMI), Ref. 5. Fringe images are projected on the blade that encode the out-of-plane deflection as fringe displacement. Moiré patterns are then produced at later time during post-processing by interfering the acquired fringe images with computational reference images at different phase shift. The resulting Moiré images can be evaluated using the well known Phase Shift Technique (Ref. 4). Drawback of the PMI method is the dependency of resolution on the fringe spacing and also the inaccuracies due to the differences of projected fringe images compared to fringes produced by interferometric light sources. The fact that Moiré planes of equal deflections are complex elliptical functions can further reduce the accuracy. The principle of using projected fringes or interferometric light patterns to determine 3-dimensional surface coordinates is well known and widely used and accepted in industry. Depending on the projection pattern, resolutions in the order of microns are possible. Complete 3-dimensional objects can be digitized by integration of several partial views from different directions. Different methods are available for various requirements of resolution, accuracy, surface complexity, surface motion, and other parameters. A very simple reconstruction at low resolution can, for instance, be obtained with the "Gray Code Method" (Ref. 4) even at complex surfaces. Higher resolution can be achieved applying the "Phase Shift Method" (Ref. 4) at simple and smooth surfaces. The combination of both methods can be very efficient and may safely produce higher resolution data. Yet, these methods can be applied at still surfaces only, as several images of the object have to be taken. For fast moving surfaces like the helicopter rotor blade one single image must be sufficient for a complete analysis. To meet this requirement there are methods like the "Fourier Method" or the "Moiré Method". Both methods have disadvantages, as reconstruction can be unsafe at complex surfaces and resolution is limited to approximately 1/10 to 1/20 of the fringe width which translates to a value of half a pixel as the fringe width can not be chosen too small.

The FCM, on the other hand, which is based on cross-correlation in frequency domain, yields a resolution of 1/10 to 1/20 pixel, an order of magnitude better than the latter methods. Draw back of this method, however, is the fact that surfaces must be smooth with no high surface gradients or steps or edges. This, however, is normally no problem at helicopter rotor blades.

Using the FCM, blade surface deflections of a amount of 1/10,000 of the image size can be detected and variations of the angle of attack of 0.075 degree. While very short shutter times allow the investigation of blade parameters at a single azimuthal position, longer shutter times enable the investigation of blade flapping over complete rotor turns.

The Fringe Correlation Method

The basic principle of the FCM is the projection of some constant light pattern on the surface at a large angle relative to the surface normal vector. A deflection of the surface in direction of the normal vector will result in a displacement of the projected pattern that can be detected by an image analysis system. Knowing the geometrical set-up of camera and projector, the deflection can be reconstructed with the simple formula shown in figure 1.



$$\boxed{\text{deflection} = (\cos\beta / \sin(\alpha + \beta)) * \text{image shift}}$$

Figure 1 : Principal set-up of the FCM for rotor investigation.

This figure also shows the principal set-up of the FCM for rotor investigation. The camera is mounted below the rotor directly facing the lower blade surface. The angle alpha relative to the z-coordinate should be small for minimizing geometrical image distortions and depth of field problems. The projector is located to project its pattern image from a large angle beta relative to the z-coordinate, i.e. at a small angle relative to the surface. The larger beta is chosen, the larger an amplification factor of the blade deflection can be obtained. At, for example, beta of 45 degree and alpha of 0 degree, this FCM-factor is exactly one, i.e. a pattern displacement represents directly the vertical surface deflection.

Principally it is possible to use complex 2-dimensional patterns for projection, and projector and camera locations extending in full 3-dimensional space to detect deflections of complex surfaces in any direction. For the rotor blade measurement, however, vertical blade surface deflections are measured only. A set-up with location of projector, camera, and triggered blade azimuth in one single plane, and a simple coarse fringe pattern with the fringes extending perpendicular to this plane gives the best results. Any surface motion within the surface itself can, of course, not be detected from pattern displacement, but from tracking of leading and trailing edge of the blade in the images.

As this set-up is useful for one single blade azimuth position only, projector and camera are mounted on a turn-table having the same rotation axis as the rotor, see figure 2.

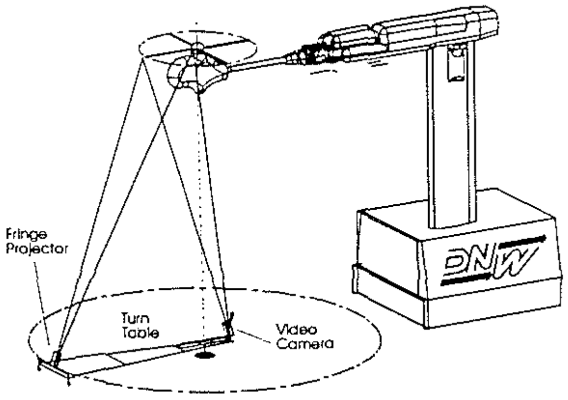


Figure 2: FCM set-up for helicopter rotor investigations in the open jet wind tunnel configuration of the DNW.

The turn-table is adjusted in small steps, say 10 or 15 degree, to provide deflection data for the complete rotor azimuth. Exact positions and viewing angles of projector and camera must be available to obtain accurate data. In the DNW, for instance, these data are measured by means of theodolites and provided as x-, y- and z-coordinates of all FCM-components in the Cartesian tunnel system. However, if these cannot be provided, a calibration of the system is possible and necessary by using two reference images at known deflection.

As the blade rotates at high speed, the camera operates at a very short shutter time of 100 microseconds. At this shutter time either a very powerful slide projector or an amplified camera has to be used. Some image noise from amplification can be observed in the images presented in this paper. Yet it is not a problem as local deflections are averaged over certain rectangular regions (windows) that are larger than the noise pattern.

The FCM uses a cross-correlation algorithm for displacement detection. Therefore a reference image at known position must be provided. This can be a no-lift case or even a non-rotation configuration. It is even possible to use an artificial reference image with a fringe pattern calculated for a special basic blade position. Cross-correlation is done in frequency domain using small rectangular windows that are thin in chordwise direction and relatively large in spanwise direction. The window should cover at least two fringes, better three or four, to minimize border effects. Using windowing functions like Hamming may result in an improvement, depending on fringe pattern and window size. The cross-correlation peak is detected by applying a polynomial curve-fitting algorithm. To improve the accuracy of the method, a second pass of the algorithm uses new correlation windows shifted by the integer result from the first pass. Maximum resolution of this method is 1/20 pixel.

If, as usual, regular fringe patterns are applied, displacements of up to half the fringe pair width can be detected. If displacements are known to be larger a direction ambiguity arises. This ambiguity can be solved by additional knowledge like the displacement at one single location of the blade. To accomplish this, one of the fringes is marked, for instance by having a different width, or a little scratch, or any other distinguishable mark. Given this marker position in the images, the system can predict basic displacements and can shift the correlation windows accordingly. This way even very large deflections can be measured safely with no ambiguity.

The detected displacement is an average value of the rectangular correlation window, which can be placed on any location of the blade surface. Displacement vectors are calculated on a rectangular grid covering the complete blade surface. If blade torsion has to be measured, very thin correlation windows allow measuring close to trailing or leading edge. Results can be displayed as deflection vectors, iso-deflection lines, gray-level or color calibrated deflection surfaces, or even in perspective projections of the 3-dimensional deflection.

Accuracy

As mentioned before, the maximum resolution of the method is 1/20 pixel. Depending on image noise, surface gradients, surface cleanness, light pattern steadiness, and, of course, accuracy of the geometrical set-up and repeatability of the turntable position, the final accuracy is lower, possibly 1/10 pixel. Using this value as a basic resolution, a geometrical FCM-factor from set-up of one, and a normal 768*512 pixel CCD-video camera, the geometrical resolution is approximately 1/7,500 of the image size horizontally. At a model rotor of 2 m radius this results in a resolution of 0.26 millimeters. At a blade chord length of 0.2 m, for example, this results in a smallest detectable change of the angle of attack of 0.075 degree. This resolution can be increased by using higher resolution cameras (1280*1024 pixel), high power slide projectors (up to 7000W with 85,000 Lumen illumination) and perfect clean and smooth surfaces.

For the helicopter rotor investigation, an additional decrease of accuracy may result from body vibration or motion. Two additional cameras were used during the measurement having a stereometrical view of the helicopter body. Special illuminated markers on the body could be tracked by those cameras simultaneously with acquiring the FCM images for later correction of the results. Vibration amplitude was found to be approximately 1 mm at very low frequency. The resolution of this body tracking and therefore the accuracy of the correction depends on the marker size. While very small markers provide a one pixel resolution only, larger markers can be detected at a resolution of up to 1/10 of a pixel, approaching the same accuracy as the FCM itself.

The Experiment

The FCM was used in the LLF of the DNW wind tunnels for an investigation of the effect of higher harmonic control (HHC) at a 4 m diameter helicopter rotor. Tip speed was 200 m/s, HHC configuration was 6/rev (i.e. 6 sinus cycles per revolution) at an amplitude of 0.6 degree (i.e. maximum pitch deflection during one sinus cycle) and a phase shift of 0 degree (i.e. sinus cycle begins at 0 degree azimuthal angle). Different reference images have been acquired at non-rotating configuration, no-lift configuration in basic position, then in a position shifted by 2 cm vertically for calibration, and finally at the basic flight configuration with HHC off (base line) and the HHC test configuration. Images were acquired at 15 degree azimuthal steps using the turn-table, see figure 2. Images for base line and HHC configuration were acquired without switching off the rotor or moving the turntable to provide the maximum accuracy for comparison.

The camera shutter is triggered by the rotor position. All images, including the two images of the additional cameras for position correction, were acquired into computer memory at video real time. As the rotor frequency was slower then video real time, intermediate FCM-images are taken from internal camera memory. 5 FCM images and 5 position images for each azimuthal step and each configuration are stored on hard disk for later processing.

Results

For analysis all images have been enhanced to have similar contrast range. A Gaussian filter with 3*3 kernel size was applied to decrease noise. The surface deflection of regular flight (base line) and HHC configuration are calculated by correlation with the reference images. Also a direct comparison between base line and HHC case was conducted. An example for the relatively noisy fringe images is presented in figure 3, showing the no-lift reference position at the top, base line case in the center, and HHC case at the bottom. See the marker, a simple scratch on the fringe pattern slide, at the right hand side. As deflections for HHC, when compared to the base line case are very small, a fringe displacement is hardly visible here.

Figure 4 shows the gray-coded deflection of base line case or HHC case relative to the reference position. The scale is calibrated in millimeters, upward deflection being positive. The large flapwise deflection of the blade with the maximum at the tip results from the lift of the rotor. To be able to see the difference between base line and HHC case, the HHC image was directly correlated with the base line image, shown in figure 5 for an azimuthal angle of 150 degree and in figure 6 for 90 degree azimuthal angle. For these azimuthal position a slightly larger angle of attack at the blade tip can be detected. However, the elastic deflection differences between base line case and HHC are small. This seems reasonable due to the fact that the HHC part of the pitch settings at these particular azimuthal angles are equal to zero corresponding to a 6/rev-HHC setting at zero phase angle shift.

Another example shows the flapping of the blade over a large azimuthal range . Using a long shutter time, the fringe pattern is visible on the blade surface over the complete illuminated region (Fig. 7). This technique allows to determine the locally averaged out-of-plane deflection. In case of helicopter rotor blade investigations the averaged blade flapping distribution can be achieved by correlating the corresponding images. Figures 8 and 9 show the effect of HHC versus the base line case on the blade flapping; figure 10 represents the difference of the elastic flapping between the HHC minimum-noise and HHC minimum-vibration cases of the first HART campaign in the LLF of DNW (Ref. 3).

Conclusion

The "Fringe Correlation Method" FCM has been developed for deflection measurement of fast moving surfaces. It has been successfully tested at a HHC rotor investigation in the DNW windtunnel. Using the FCM, the complete 3-dimensional blade surface could be measured at high accuracy and variations in flapping and torsion of the blade due to the influence of HHC, for instance, could be detected at selected azimuthal angles.

It seems possible that measurements can be performed even in real flight conditions, projecting the fringes from a side window of the helicopter and mounting the camera on the landing gear or on a specially designed pylon. At complete darkness during night time a powerful fringe projector should guarantee visible fringe images on the lower blade surface even with very large blades. A special asymmetric projector lens can be used to compensate for the very small angle between optical projector axis and blade surface.

References

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Ref.4: Osten W., "Digitale Verarbeitung und Auswertung von Interferenzbildern," Akademie Verlag GmbH, Berlin 1991.

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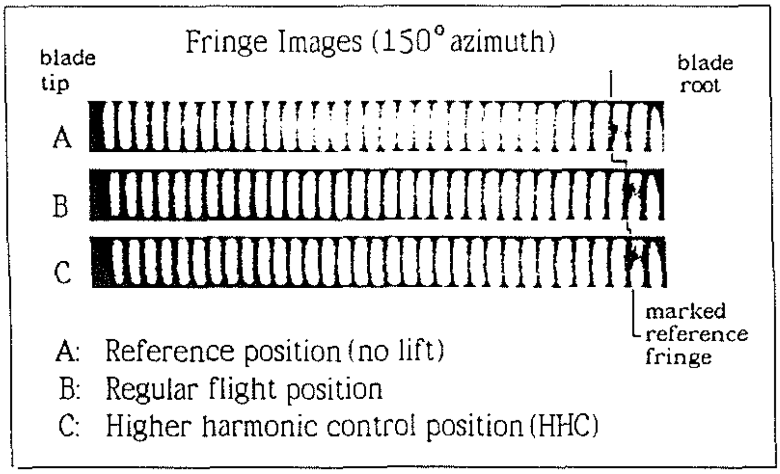


Figure 3: Fringe images for different flight conditions.

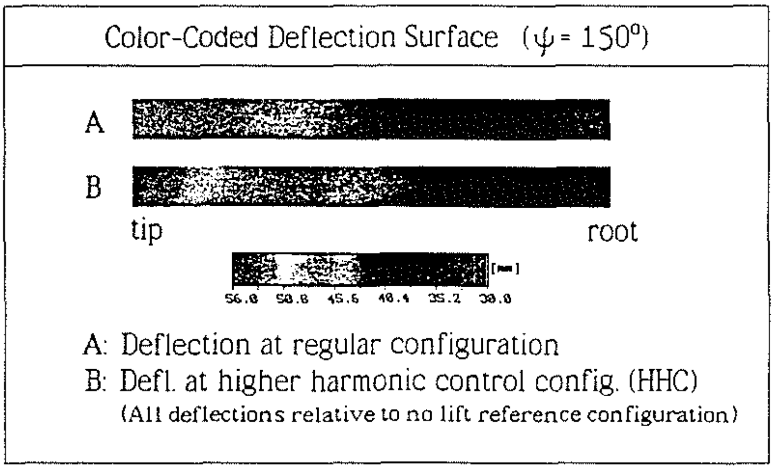


Figure 4: Blade deflections at base line and at HHC configurations.

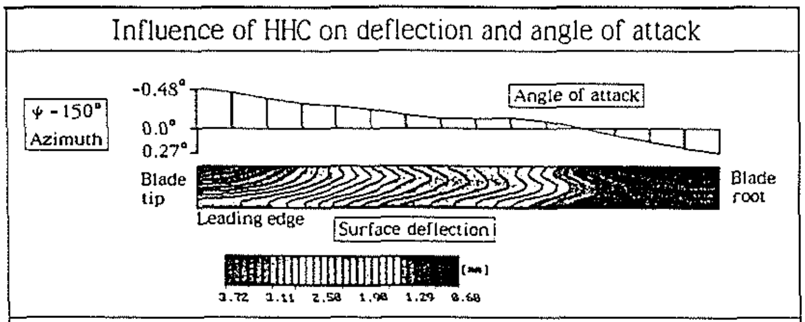


Figure 5

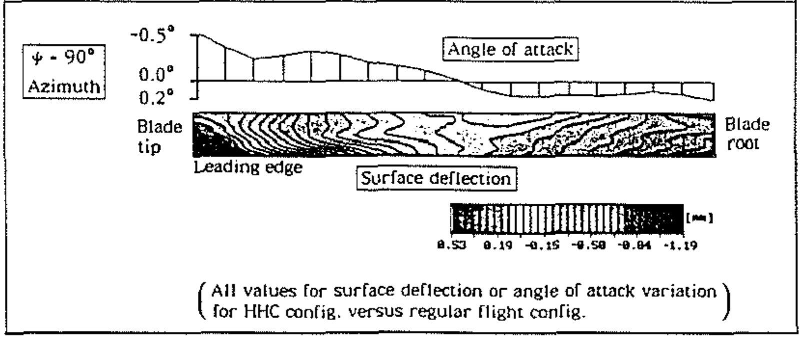
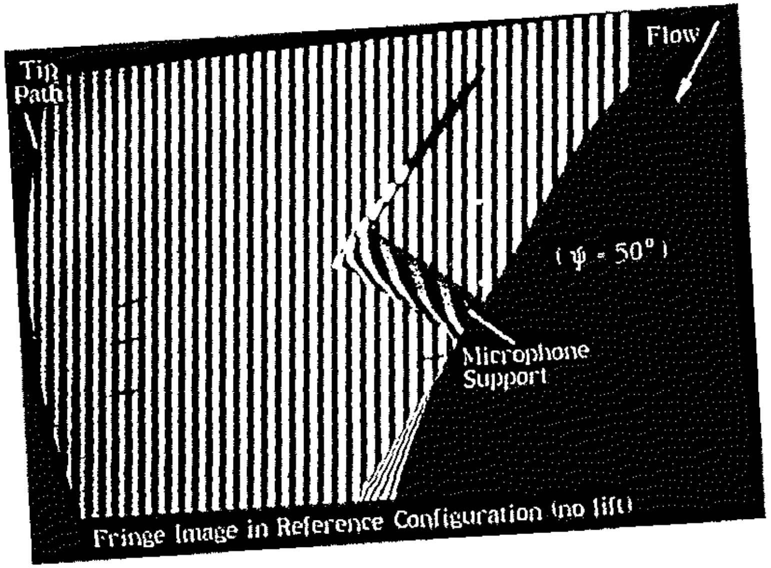


Figure 6

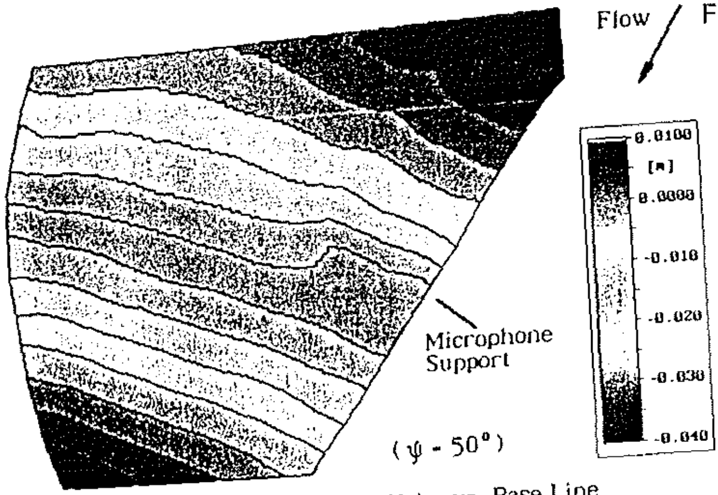
Influence of HHC at different azimuth positions.

Fig. 7



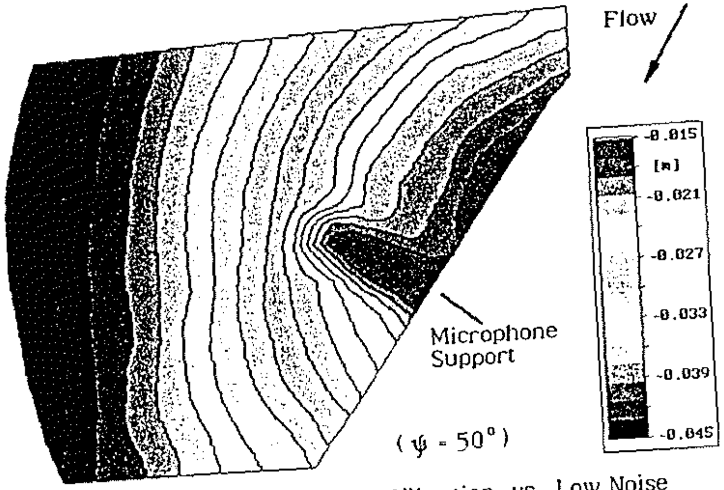
Fringe Image in Reference Configuration (no lift)

Fig. 8



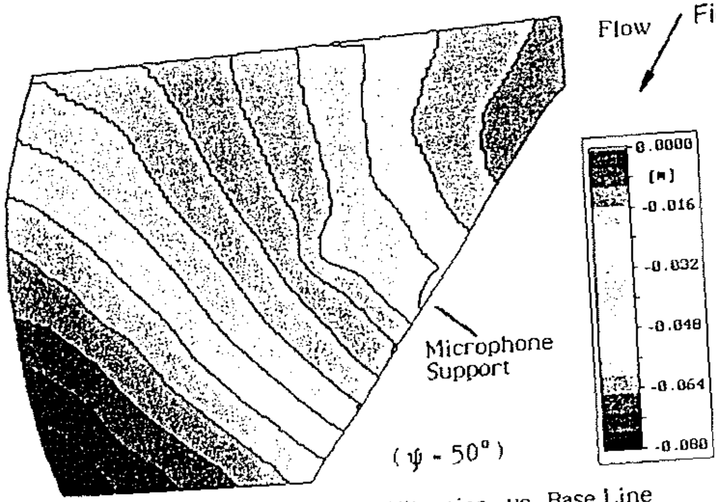
Rotor Disk Deflection: HHC Low Noise vs. Base Line

Fig. 10



Rotor Disk Deflection: HHC Low Vibration vs. Low Noise

Fig. 9



Rotor Disk Deflection: HHC Low Vibration vs. Base Line

Full rotor disk deflection: Comparison of base line, HHC minimum noise and HHC minimum vibration.
Advance Ratio = 0.15, Rotor Radius = 2m, Wind Velocity = 33m/s, Rotor Speed = 1050rpm, Shaft Angle = 5.3 deg., 3P- HHC