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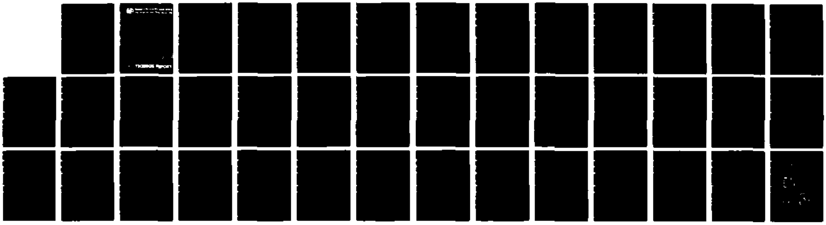

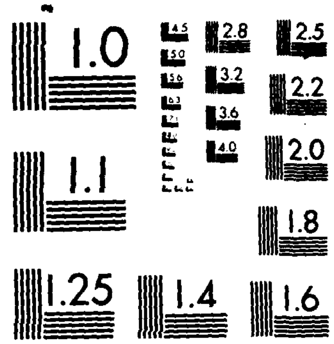

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THE EFFECTS ON ROTOR NONUNIFORM INFLOW
HARMONIC CONTENT OF UNEVEN CIRCUMFERENTIAL
DISTRIBUTION OF JET ENGINE INLET GUIDE VANES

by

Margaret R. Hinsman

ARL-PSU

TECHNICAL REPORT

The Pennsylvania State University
Intercollege Research Programs and Facilities
APPLIED RESEARCH LABORATORY
P. O. Box 30
State College, PA 16804

THE EFFECTS ON ROTOR NONUNIFORM INFLOW HARMONIC CONTENT OF UNEVEN CIRCUMFERENTIAL DISTRIBUTION OF JET ENGINE INLET GUIDE VANES

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A computative parametric study was conducted to investigate the effects of vane section geometry, vane number, and primarily, uneven circumferential vane spacing on the harmonic content of the wake field produced by a row of jet engine Inlet Guide Vanes (IGV). As parameters were varied, the harmonic content of the resulting wake field was analyzed for its potential effect on unsteady pressures at the rotor. A semi-empirical model is presented which was used to generate the two-dimensional flow field downstream of the IGV

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plane. Results show that uneven angular spacing of IGV should not be employed for reducing unsteady pressures experienced by the rotor. In fact, manufacturing tolerances, relative to IGV angular location, of evenly spaced vanes should be minimized to minimize unsteady pressures.

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Abstract

A computative parametric study was conducted to investigate the effects of vane section geometry, vane number, and primarily, uneven circumferential vane spacing on the harmonic content of the wake field produced by a row of jet engine Inlet Guide Vanes (IGV). As parameters were varied, the harmonic content of the resulting wake field was analyzed for its potential effect on unsteady pressures at the rotor. A semi-empirical model is presented which was used to generate the two-dimensional flow field downstream of the IGV plane. Results show that uneven angular spacing of IGV should not be employed for reducing unsteady pressures experienced by the rotor. In fact, manufacturing tolerances, relative to IGV angular location, of evenly spaced vanes should be minimized to minimize unsteady pressures.

Acknowledgements

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Nomenclature

A_0	Fourier cosine amplitude of the zeroeth harmonic
A_N	Fourier cosine amplitude of the Nth harmonic
B	number of inlet guide vanes
B_N	Fourier sine amplitude of the Nth harmonic
c	vane section semichord
C_D	vane section drag coefficient
C_N	Fourier modulus
D	percent deviation of unevenly spaced IGV from evenly spaced IGV
m	positive integer
n	summing index
N	harmonic order
r	radial coordinate
u_c	wake centerline velocity
u_t	resultant wake field velocity
V	vane section inlet relative velocity
x	axial coordinate when $\alpha = 0$
Y	wake halfwidth
α	vane section stagger angle
θ	tangential coordinate
Θ	angular spacing between evenly spaced vanes
Θ_i	angular spacing between unevenly spaced vanes
$\Delta\Theta$	maximum difference between vane spacing of unevenly spaced IGV from evenly spaced IGV of the same vane number
ϕ_N	Fourier phase angle of the Nth harmonic

INTRODUCTION

A jet engine rotor blade when operating in a spatially varying flow field will experience unsteady pressures due to the ingested nonuniform velocity field. Markedly increased levels of structural vibration, blade fatigue, and radiated sound result from unsteady forces and moments produced by the unsteady pressures. A Fourier transform of the unsteady inflow to the rotor yields valuable information about the unsteady forces and moments likely to be experienced by the rotor, as they are functions of the inflow harmonic content.

The spatial variation in a flow field of a jet engine rotor is heavily influenced by upstream appendages. The viscous wakes shed by a row of inlet guide vanes (IGV) produce a fertile nonuniform flow field for unsteady forces and moments. A conventional IGV configuration, in which the angular spacing of the vanes is even circumferentially, produces a periodic nonuniform flow field in which the rotor operates. Fourier analysis of this flow field yields prominant Fourier amplitudes at harmonics equal to the number of IGV and multiples, implying energy concentrations at these wave numbers. A rotor operating in this flow field will experience unsteady pressures, proportional to Fourier amplitudes and a function of harmonic phase, at all frequencies. Summation of these unsteady pressures over the blade span and chord and then over all blades results in unsteady forces and moments at frequencies equal to blade number times rotor RPS and multiples. Magnitudes of these forces and moments are proportional to inflow Fourier amplitude and a function of inflow harmonic phase at harmonics equal to number of rotor blades and multiples.

The primary objective of the present investigation was to determine the effects of altering the harmonic content of the rotor inflow by employing unevenly spaced IGV. Examination of the harmonic content was intended to provide answers to the following questions:

1) Is altering the harmonic content of the rotor inflow in this manner beneficial relative to reducing unsteady pressures experienced at the rotor?

2) If not, then what effect do manufacturing tolerances have on harmonic content of the rotor inflow produced by conventional IGV configurations, as perfectly even vane spacing in reality is impossible?

Shahady, et al., [1] performed a similar study on effects of uneven rotor blade spacing on radiated sound pressure level and rotor performance. While they found that uneven rotor blade spacing reduces peak amplitudes of the rotor harmonics, the dynamics problem of an asymmetrically weighted rotor could be circumvented if uneven IGV spacing achieves similar results.

A computative parametric study was conducted to investigate the effect of vane section geometry, vane number, and primarily the circumferential vane spacing on the harmonic content of the wake field produced by a row of IGV. A semi-empirical method is presented which was used to generate the two-dimensional flow field downstream of the IGV plane. As parameters were varied, analysis of the harmonic content of the resulting nonuniform flow field yielded a judicious recommendation for IGV configuration to minimize unsteady pressures experienced by the rotor.

GENERATING THE WAKE FIELD

The computational model adopted in this study for generating the viscous wakes of the IGV was developed by Sears and Kemp [2] with the aid of empirical relationships developed by Silverstein, Katzoff, and Bullivant [2], who experimentally measured isolated airfoil wakes and generalized their results.

Sears and Kemp, assuming that the wakes behind each vane are identical to that behind an isolated airfoil, used the results of reference [3] to develop a set of equations which completely defines the viscous wake field generated by an infinite cascade of vanes.

The adopted model can be clarified with a schematic of an infinite cascade (Figure 1). Each vane is of chord 2c, stagger angle α, and angular spacing Θ from adjacent vanes. A viscous wake, of width 2Y and centerline velocity u_c, forms behind each vane as the fluid flows with relative inlet velocity V over the vanes. Thin airfoils with zero camber have been assumed. Sears and Kemp further assumed that the wakes are inviscid, symmetric shear perturbations in the otherwise uniform flow. These perturbations appear as symmetric velocity deficits in the velocity field shown downstream of the cascade.

The model derived in reference [1] can be summarized by three equations. The first defines the wake half-width as a function of x, developed by Silverstein, Katzoff, and Bullivant:

$$Y = .68\,\sqrt{2}\,c[C_D(x-.7c)/c]^{1/2} \tag{1}$$

where C_D is the section drag coefficient and x is the distance measured from the trailing edge of the vane along the wake axis to the point of the desired velocity distribution; note that the x coordinate is oblique to the θ coordinate if $\alpha = 0$. The second relationship is the centerline velocity as a fraction of inlet relative velocity and a function of x, given in reference [2] in the form:

$$\frac{u_c}{V} = -(2.42\,\sqrt{C_D})/(\frac{x}{c} + .3) \tag{2}$$

Finally, assuming that the wake field behind a cascade can be described by superposition of individual airfoil wakes, Sears and Kemp give the total perturbation velocity field as a fraction of centerline velocity and function of x and y, or in cylindrical coordinates, a function of x and θ.

$$\frac{u_t}{u_c} = \sum_{n=-\infty}^{\infty} \exp\left[-\pi \left(\frac{r \cos\alpha}{Y}\right)^2 (\Theta - \Theta_i)^2\right] \tag{3}$$

r is the distance between the IGV central axis and the vane section under consideration.

In the present investigation the effects of vane section geometry (C_D), number (B), and spacing (Θ_i) on the harmonic content of the inflow to a rotor were studied. The given model depends on parameters other than those studied in this investigation, i.e. r, α, c, and x. Throughout this investigation these parameters were kept at the following nondescript values: r = 1.0, α = 0 degrees, c = 1.0, x = 2c.

Equations (1), (2), and (3) comprise the model for defining completely the two-dimensional perturbation velocity as a fraction of inlet relative velocity due to the viscous wakes shed from an IGV plane of B vanes. While the many assumptions in the development of the adopted model detract from the accuracy of approximating wake fields, for the purposes of Fourier analysis the appropriate trends of the amplitudes and phase angles with changes in geometric and flow variables are accurately predicted. Because this study is concerned with the trends of the harmonic content of wake fields as parameters are varied over wide ranges, a moderately accurate model, while simple and easily manipulable, is preferred.

GENERATING THE HARMONIC CONTENT

In the present investigation the effects of vane section geometry (C_D), number (B), and spacing (Θ_i) on the harmonic content of the inflow to a rotor were studied. As each parameter was varied, a circumferential axial velocity distribution was generated according to the given model and subsequently expressed as an infinite sum of weighted sinusoids in the familiar form:

$$\frac{u_t}{V} = \frac{1}{2} A_0 + \sum_{N=1}^{\infty} \left[A_N \cos(N\theta + \phi_N) + B_N \sin(N\theta + \phi_N)\right] \qquad (4)$$

where A_0, A_N, and B_N are defined in the normal way. The Fourier modulus C_N and phase ϕ_N,

$$C_N = \left[A_N^2 + B_N^2\right]^{1/2} \qquad (5)$$

$$\phi_N = \tan^{-1}\left(\frac{B_N}{A_N}\right) \qquad (6)$$

completely describe the harmonic content of the flow field. In observance of the Nyquist criterion, harmonic content of up to wave number thirty (30) was analyzed and is presented. This range will be shown to be sufficient for the development of the desired trends in the harmonic content. As harmonic phase is not a function of vane section geometry or the vane number, only the effects on Fourier amplitudes of vane section geometry and vane number are presented.

EFFECTS OF VANE SECTION GEOMETRY

The effect of vane geometry on the Fourier amplitudes of the wake field was studied collectively in terms of the section drag coefficient C_D. With uniform vane spacing and constant vane number at an arbitrary value of B=5, the drag coefficient was varied through a range .004 to .02, incorporating a wide variety of airfoil sections and flows of a variety of Reynolds numbers.

Wake fields were generated at vane drag coefficients .004, .012, and .02 and Fourier analyzed (Figure 2), marking the minimum, middle, and maximum C_D of the given range. Because equal vane spacing creates periodic velocity deficits, significant Fourier amplitudes occur at harmonics equal to vane number and multiples (N=mB). All other harmonics (N≠mB) theoretically have Fourier amplitudes of zero. Figure 2 shows that as drag coefficient increases, the resulting larger wake size causes an increase in the amplitudes that define the velocity distribution. The growth of Fourier amplitude is seen to be directly proportional to change in drag coefficient with a proportionality constant of approximately one.

EFFECTS OF VANE NUMBER

The effect of vane number on the Fourier amplitudes of the wake field was studied through the range B=5, 15, and 30, with constant drag coefficient and even vane spacing. Thirty vanes were chosen as the upper limit for B because of the unlikelihood that the adopted model can accurately predict the wake interactions of vanes with closer spacing. As indicated in Figure 3, an increase in the number of evenly spaced IGV reduces the occurance of large Fourier amplitudes in a given wave number range. However, the energy concentration at harmonics equal to vane number and multiple (N=mB) increases as B increases. The growth of Fourier amplitude with increasing vane number is seen to decrease as B increases.

EFFECTS OF VANE SPACING

Determination of the effect of uneven IGV spacing on the harmonic content of the inflow to a rotor was approached in the following manner: Figure 4 shows a conventional IGV configuration and an arbitrary, circumferentially uneven IGV configuration of the same vane number. If $\Delta\Theta$ represents the maximum amount by which any of the Θ_i of an arbitrary configuration differs from Θ of a conventional configuration of the same vane number then the percent deviation of the uneven configuration from the conventional is

$$D = (\Delta\Theta/\Theta) \times 100\% \tag{7}$$

Because of the infinite uneven IGV configurations for any one vane number, the effect of an uneven configuration on the harmonic content of the inflow to a rotor was not studied by the individual configuration, as with the previous two parameters, but were categorized by D, percent deviation from the conventional configuration.

Vane numbers 15, 10, and 5 were studied at identical percents of deviation (D) from conventional spacing of 4.2%, 8.3%, and 12.5%. To simplify discussion, consider first the 15-vaned configuration, whose conventional angular spacing is 24 degrees. A deviation of 4.2% corresponds to a $\Delta\Theta$ of 1 degree for 15 vanes. A particular category of unevenly spaced vane configurations has Θ_i in the range

$$(\Theta - \Delta\Theta) \leq \Theta_i \leq (\Theta + \Delta\Theta) \tag{8}$$

Therefore, at 15 vanes and D=4.2%, the range is

$$(23 \text{ deg}) \leq \Theta_i \leq (25 \text{ deg})$$

Even within this range many uneven configurations of Θ_i exist. In order to represent any B,D combination adequately, thirty arbitrary configurations of random vane spacing were generated with the imposed conditions that Θ_i falls within the given range and that at least one of the Θ_i's of each configuration is the maximum deviation, ($\Theta \pm \Delta\Theta$). The harmonic content of each of the thirty resulting wake distributions for a given B,D combination was studied collectively to determine trends, if any exist, as the vane spacing became more uneven, in other words, as D increased. This procedure was followed for each of the vane numbers.

Figure 5 gives the Fourier amplitudes of the case described above, B=15 and $\Delta\Theta$ = 1 degree. All thirty sets of C_N appear in the plot, giving the probable spread of amplitudes at each harmonic under the given conditions. Data such as that plotted in Figure 5 were obtained for the given D's of the three vane numbers, but subsequent plots of amplitude spread for a given vane number and $\Delta\Theta$ have been reduced to an average amplitude bound by the addition and subtraction of one standard deviation (see Figure 6 for the reduction of Figure 5).

Figures 6-14 give the reduced Fourier amplitude spreads for 15, 10, and 5 vanes, at deviations of 4.2%, 8.3%, and 12.5% in which the appropriate trends of the effect of uneven IGV spacing on the Fourier amplitudes have developed. These figures show that even the smallest angle deviation, $\Delta\Theta$ =1 degree in Figure 6, will impart to the flow significant Fourier amplitudes at harmonics other than those equal to vane numbers and multiples ($N \neq mB$), while those of harmonics of $N=mB$ do not decrease significantly. Trends show that for each vane number, as $\Delta\Theta$ increases, the amplitudes of the $N \neq mB$ harmonics increase, while those at the $N=mB$ harmonics decrease, until the Fourier amplitudes at harmonics $N \neq mB$ grow to meet those of harmonics $N=mB$. This trend is shown best with five vanes in Figures 12, 13 and 15. Thus for a given vane number, the effect of uneven vane spacing as spacing becomes more uneven is to reduce the peak amplitudes of the $N=mB$ harmonics, while raising all other harmonics from theoretically zero to a significant amplitude. Another obvious characteristic of Figures 6-14 is that between adjacent N=mB harmonics the Fourier amplitudes decrease to a minimum amplitude, at or near the harmonic halfway between, or $N=[mB+(m+1)B]/2$. As unsteady forces and moments experienced by the rotor are a function of the inflow harmonic content at harmonics of rotor blade number and multiples, choosing a blade number equal to the harmonic of a minimum amplitude would seem to minimize unsteady forces and moments. However, the even multiples of this harmonic correspond to maximum amplitudes.

The average Fourier amplitudes of Figures 6-14 have been combined on a relative harmonic scale in Figure 15. The curves of this figure indicate that for a given percent deviation, the Fourier amplitudes of harmonics $N \neq mB$ are similar in magnitude between corresponding peak amplitudes for all vane numbers. Also, as D increases, magnitudes of $N \neq mB$ harmonics increase while those of N=mB decrease.

Investigation of the effect of manufacturing tolerances on the harmonic content produced by evenly spaced IGV required study of a .5 degree $\Delta\Theta$, performed with vane numbers 15 and 10 whose Fourier amplitudes appear in Figures 16 and 17. These figures indicate that significantly larger harmonic amplitudes are generated from a conventional IGV configuration than the theoretically zero expected.

The effect of uneven IGV spacing on the Fourier phase angle is shown in Figure 18, in which phase angle is represented on a relative scale as Phase/N. The solid lines connect the maximum possible Phase/N at each harmonic. The net effect of randomly changing the vane spacing is to randomly change the phase at harmonics $N \neq mB$, while those of N=mB remain constant.

CONCLUSIONS

The effects of inlet guide vane section goemetry, number and spacing on the harmonic content of the inflow to a rotor have been studied and presented. The intent of this investigation has been to determine how these three parameters may effect unsteady forces and moments experienced by the rotor, as they are functions of the inflow harmonic content.

The effect of vane section drag coefficient on the Fourier amplitudes of the inflow to a rotor is evident (Figure 2). As drag coefficient increases, wake size increases, resulting in increased Fourier amplitudes. The less the IGV obstruct the inflow to the rotor, the less influence harmonic content due to IGV-flow interactions will have at the rotor. Therefore, IGV size and thickness should be minimized to minimize unsteady pressures at the rotor.

The effect of increasing vane number on Fourier amplitudes is to increase the Fourier amplitudes of the N=mB harmonics but decrease the occurrance of these significant amplitudes in a given wave number range. Figure 15 shows that the Fourier amplitudes of the N≠mB harmonics for different vane number and equal percent deviation are of similar magnitudes.

As shown in Figures 6 through 18, altering the harmonic content of the inflow to a rotor by employing unevenly spaced IGV adversely affects unsteady pressures experienced by the rotor. Fourier amplitudes at all harmonics are significant when angular deviations as small as .5 degree from even spacing exist (Figures 16, 17). Thus, not only should uneven vane spacing not be employed, but manufacturing tolerances relative to IGV angular position of conventional IGV configurations should be minimized in order to minimize Fourier amplitudes at harmonics N≠mB. Figures 16 and 17 indicate that a manufacturing tolerance of .5 degree will affect unsteady pressures experienced at the rotor significantly more than previously realized. In addition, Figure 18 indicates that no trends exist in Fourier phase angle of harmonics $N \neq mB$ for a given $\Delta\Theta$ and B. In other words, a $\Delta\Theta$ in IGV angular spacing will cause the Fourier phase to be unpredictable at harmonics $N \neq mB$ unless the precise location of each vane is known.

Finally, information similar to that contained in Figure 15 can be utilized in the design of a jet engine for judicious choice in vane number, blade number, and vane circumferential spacing so as to minimize unsteady forces and moments, and radiated sound from the rotor.

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[1] Shahady, etal., "Fan Compressor Noise Reduction," Paper No. 69-GT-9, presented at ASME Gas Turbine Conference, Cleveland, 1968.

[2] Kemp, N. H. and Sears, W. R., "The Unsteady Forces Due to Viscous Wakes in Turbomachines," Journal of Aeronautical Sciences, Vol. 22, No. 7, July 1955, pp. 478-483.

[3] Silverstein, A., etal., "Downwash and Wake Behind Plain and Flapped Airfoils, NACA Refs. 651, 1939.

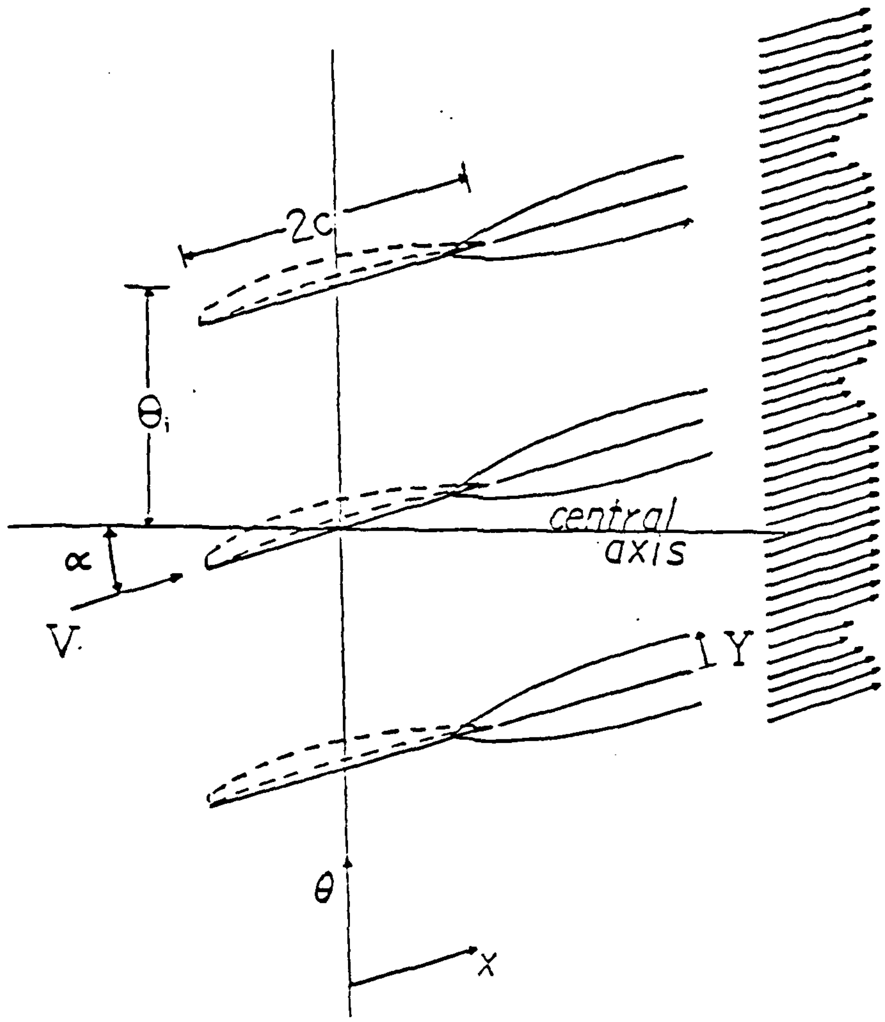


Figure 1. Schematic of Flow About an Infinite Cascade

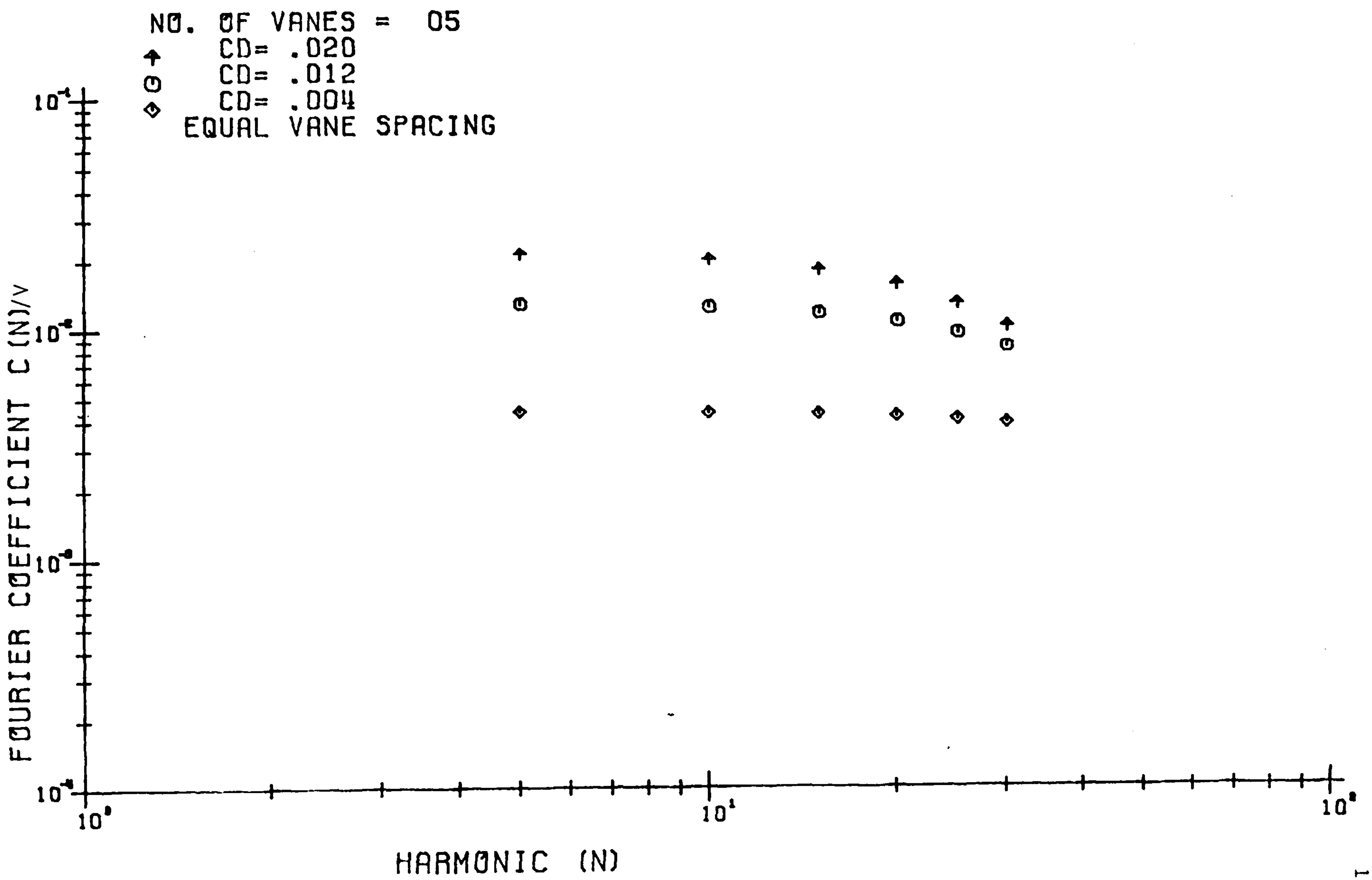


Figure 2. Effect of Drag Coefficient on Fourier Amplitudes

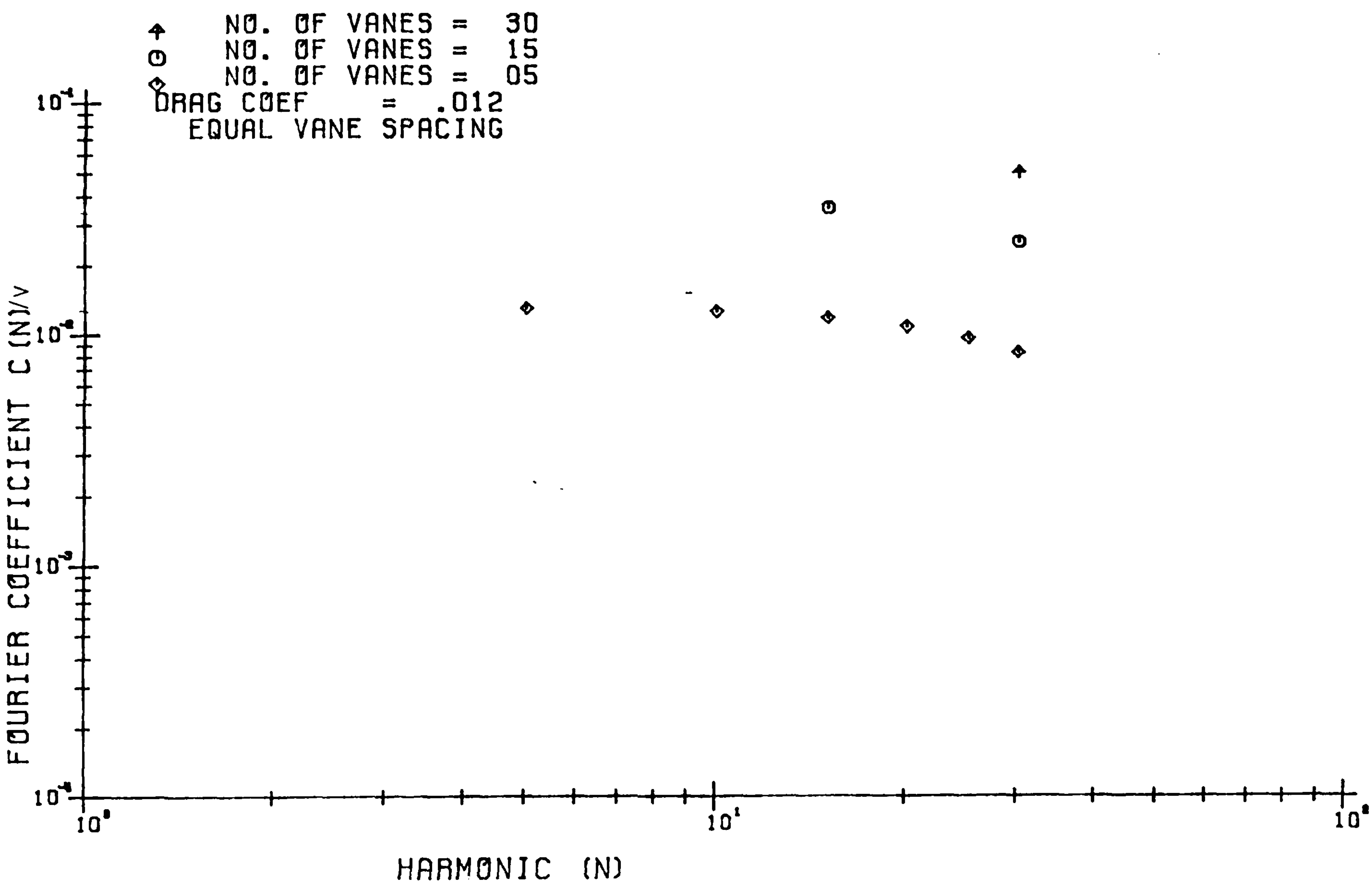


Figure 3. Effect of Vane Number on Fourier Amplitudes

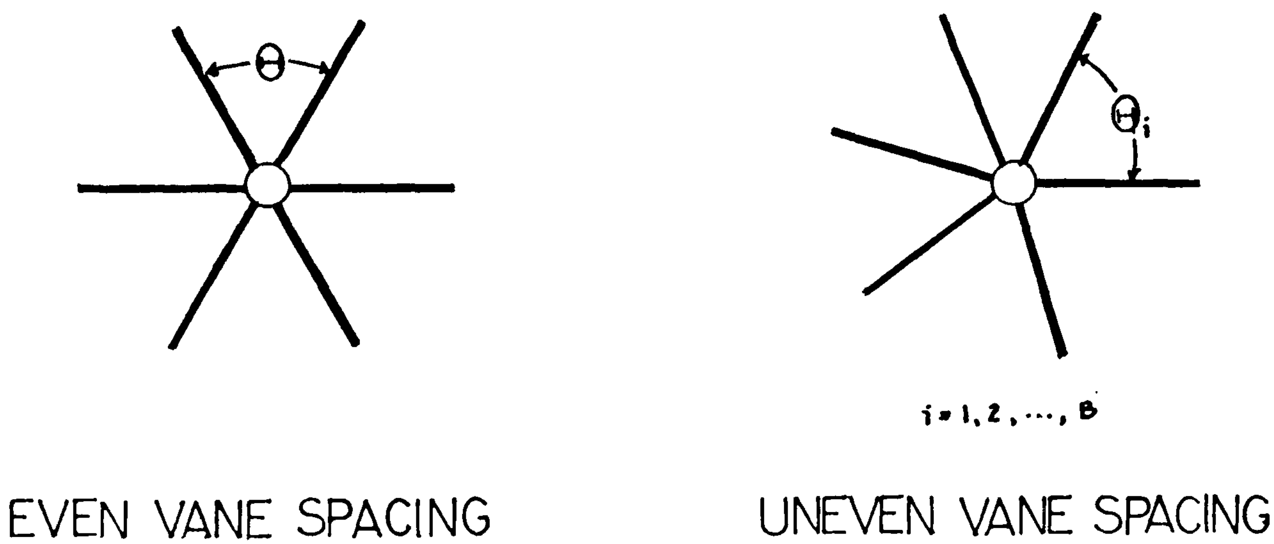
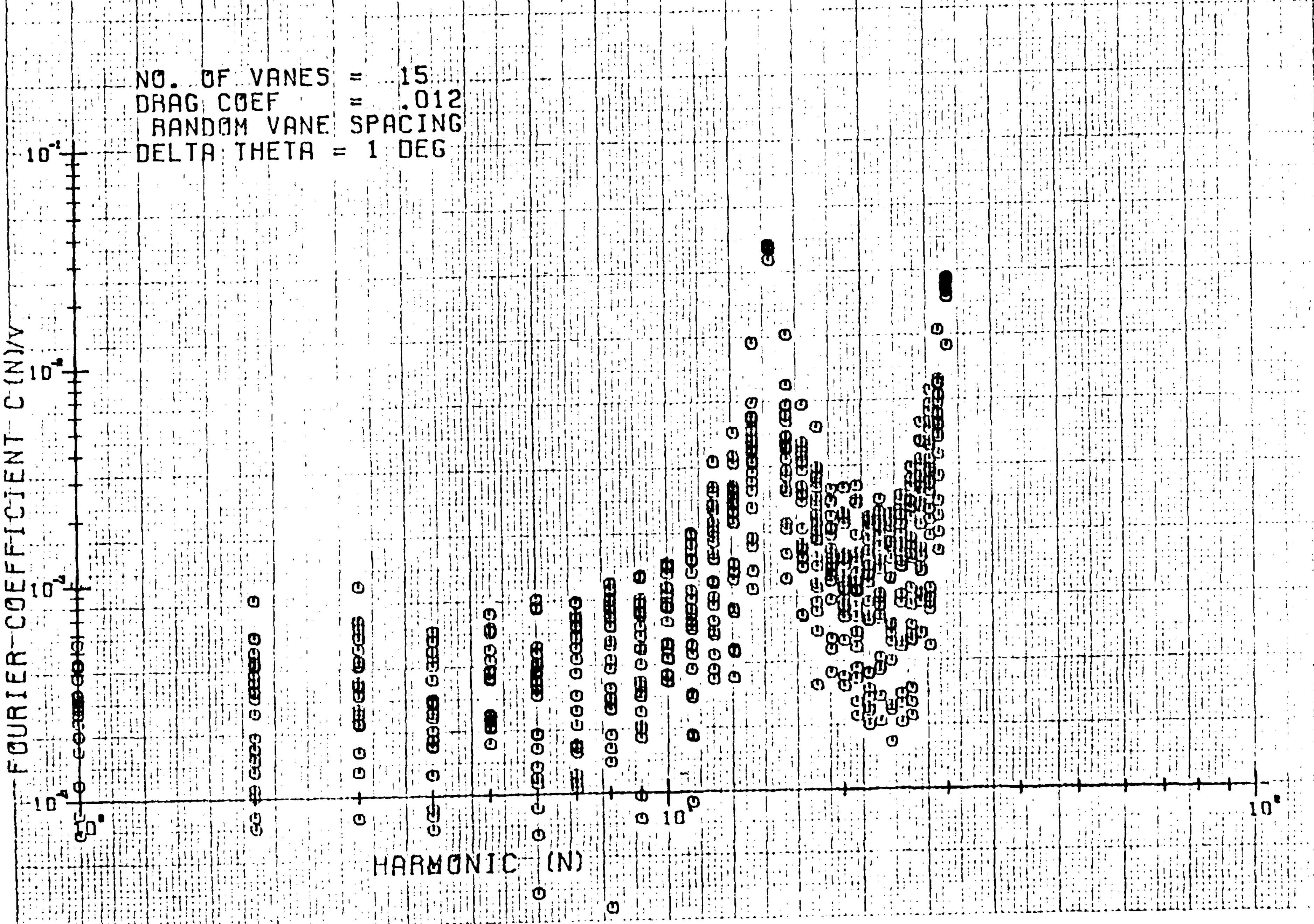


Figure 4. A Conventional and Unevenly Spaced Set of Inlet Guide Vanes

Figure 5. The Effect of Unevenly Spaced IGV on Fourier Amplitudes (Raw Data), Deviation = 4.2%



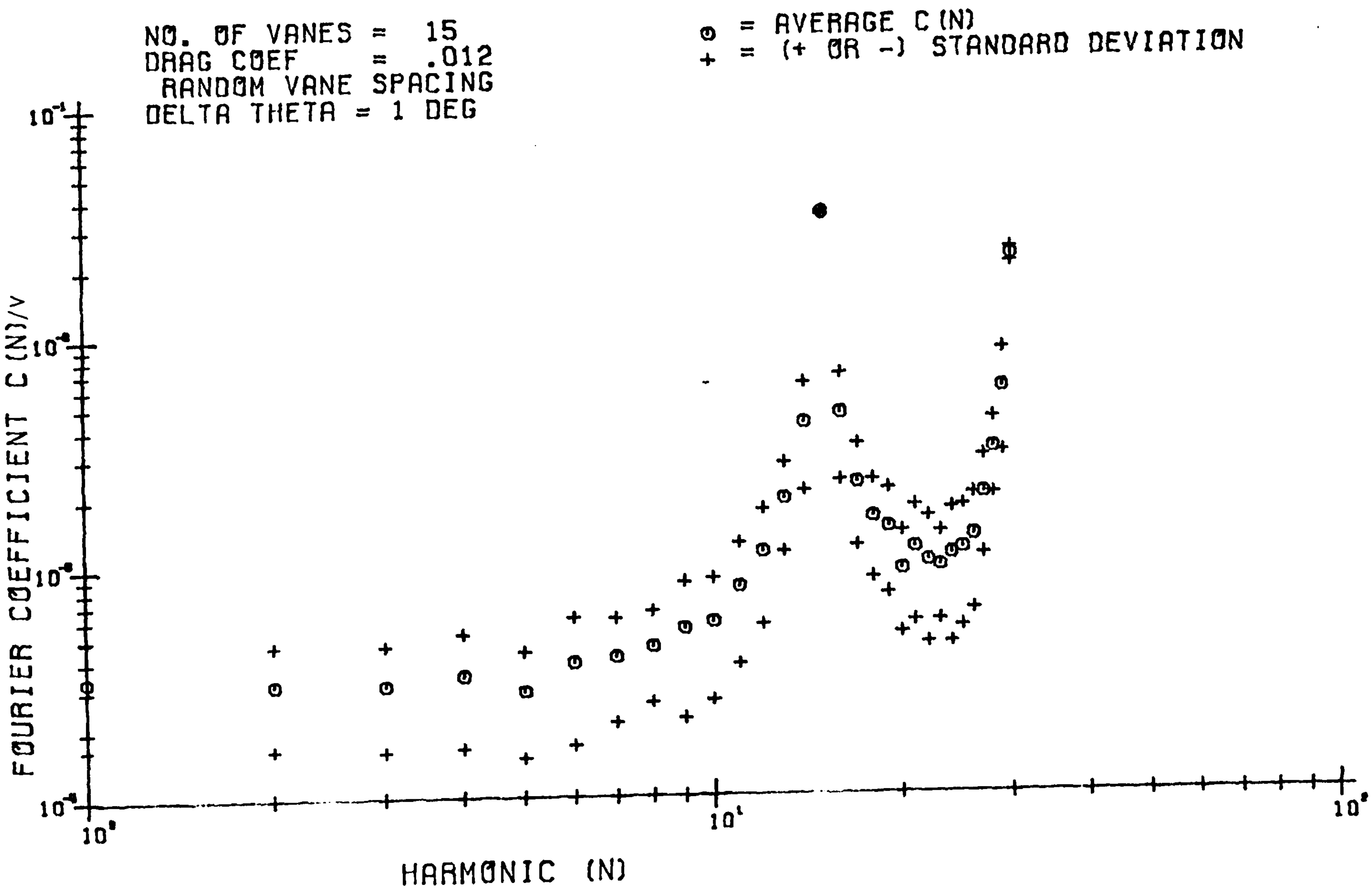


Figure 6. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 4.2%

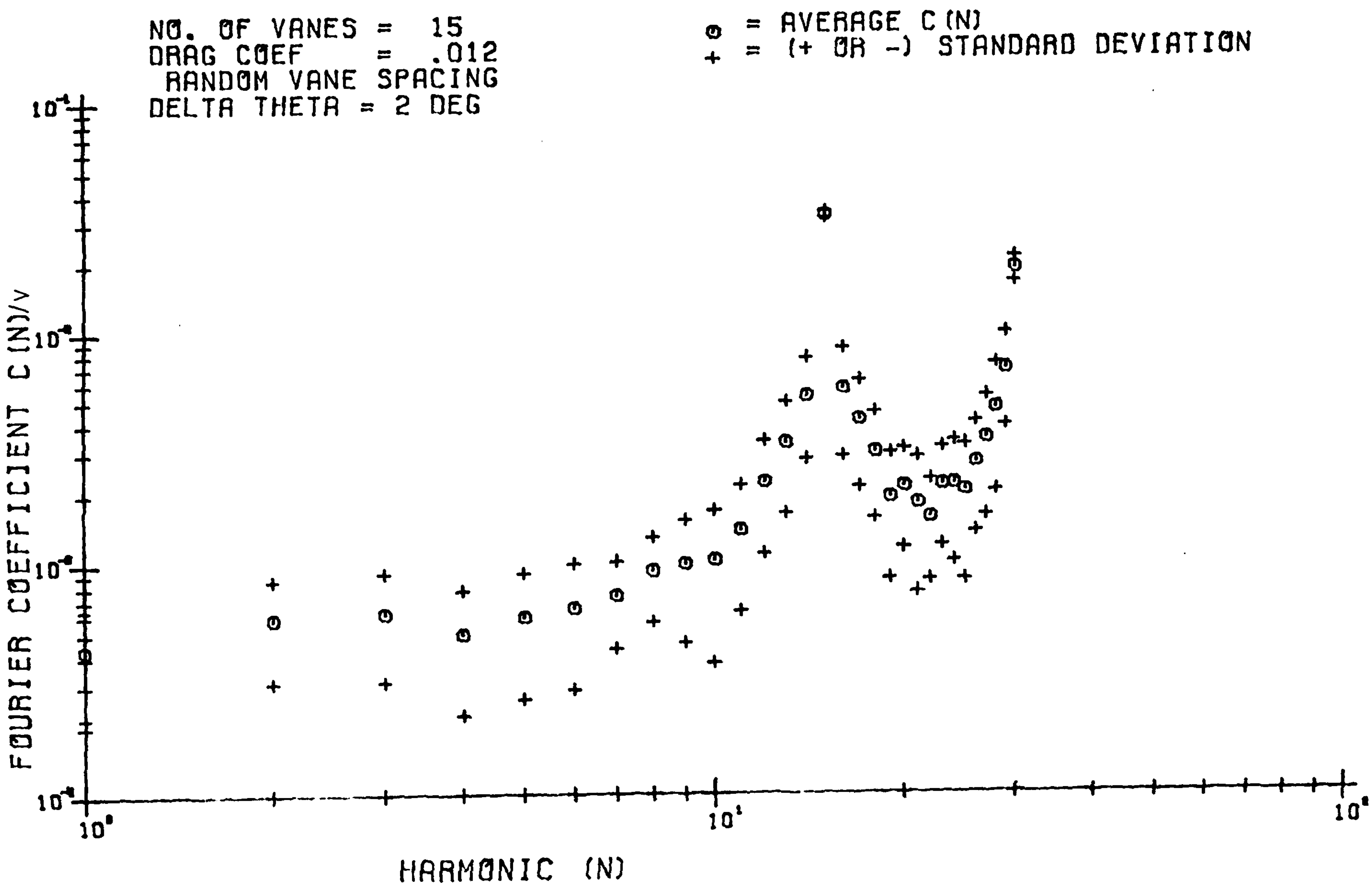


Figure 7. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 8.3%

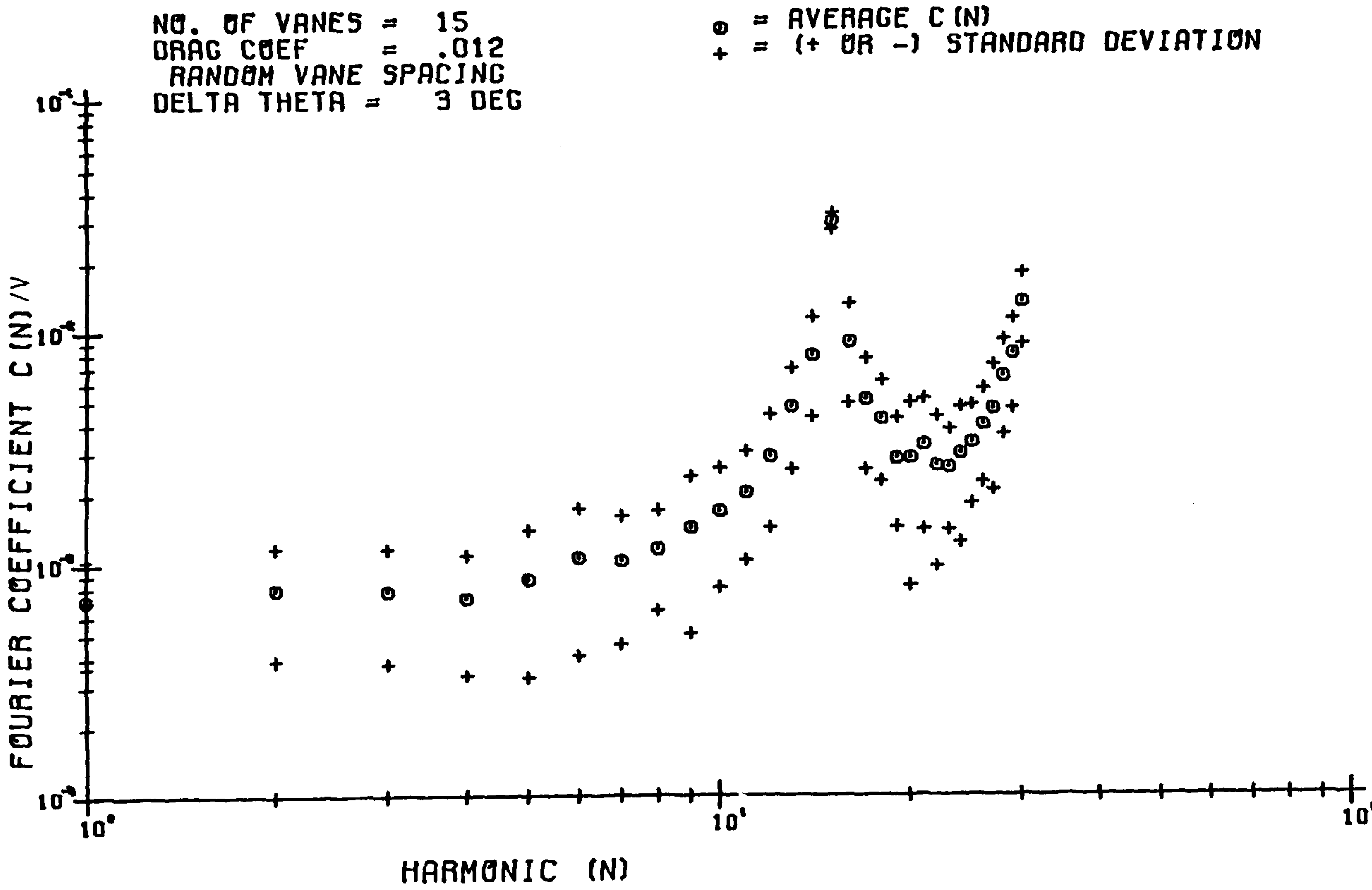


Figure 8. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 12.5%

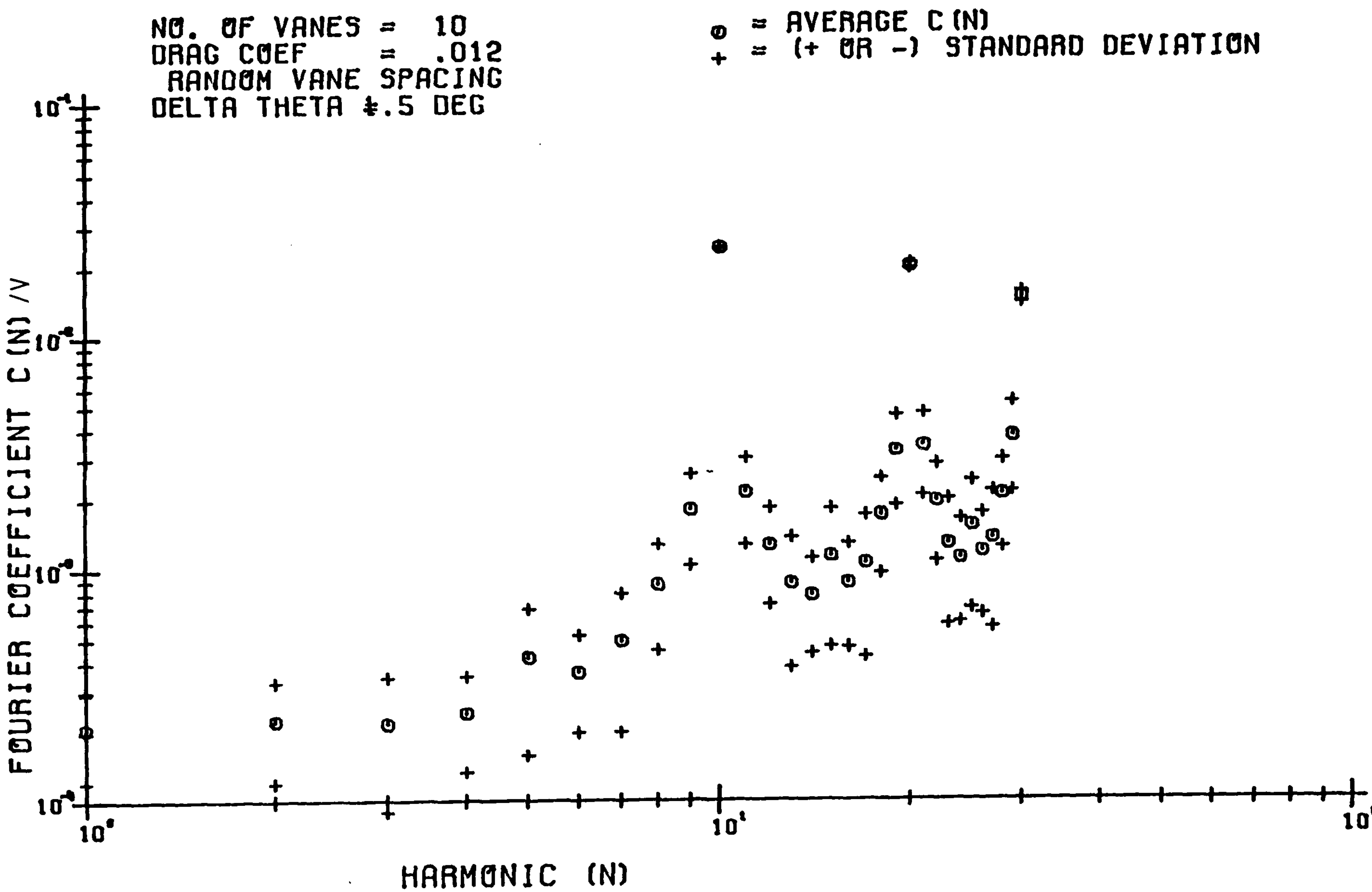


Figure 9. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 4.2%

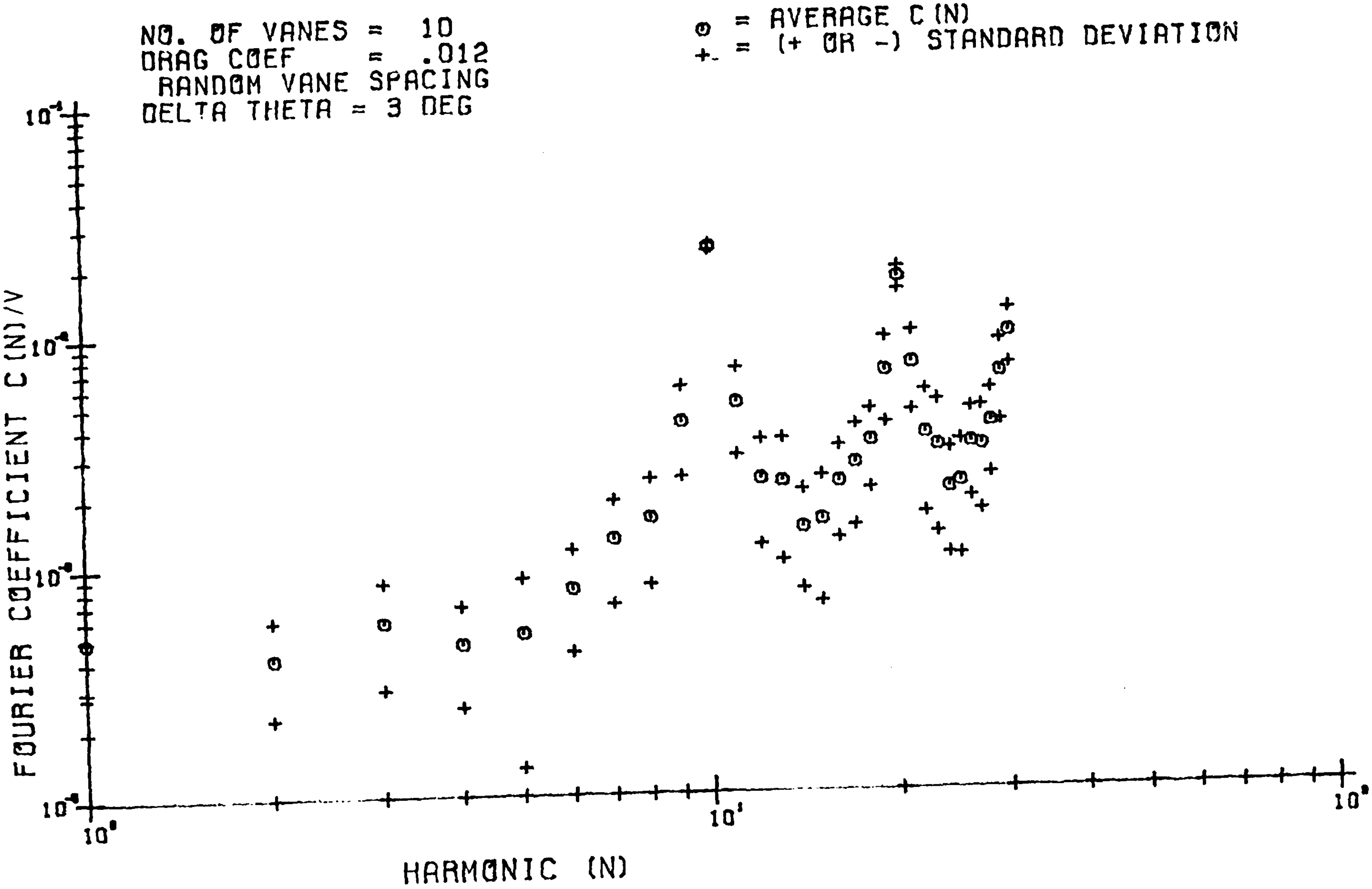


Figure 10. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 8.3%

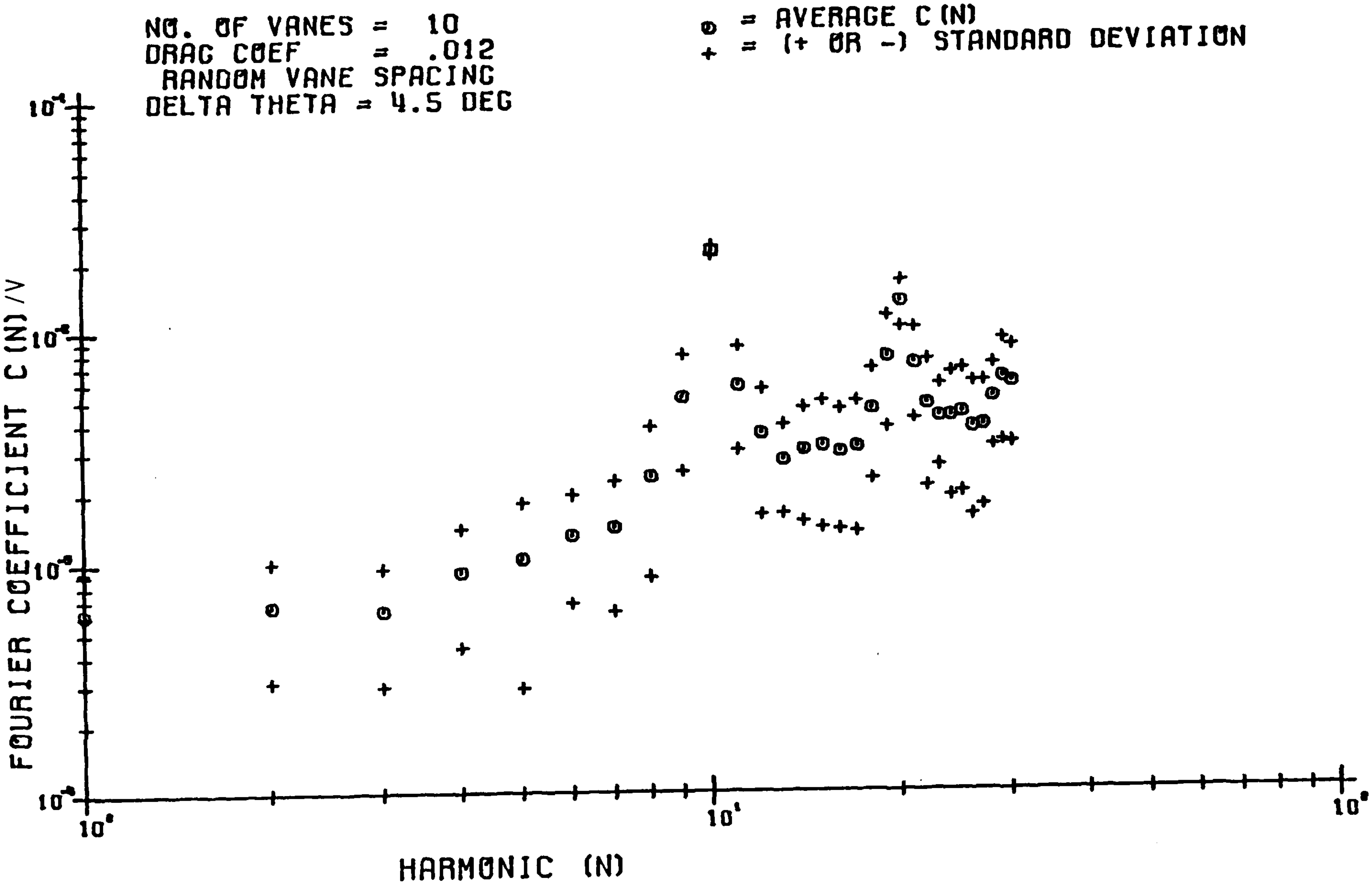


Figure 11. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 12.5%

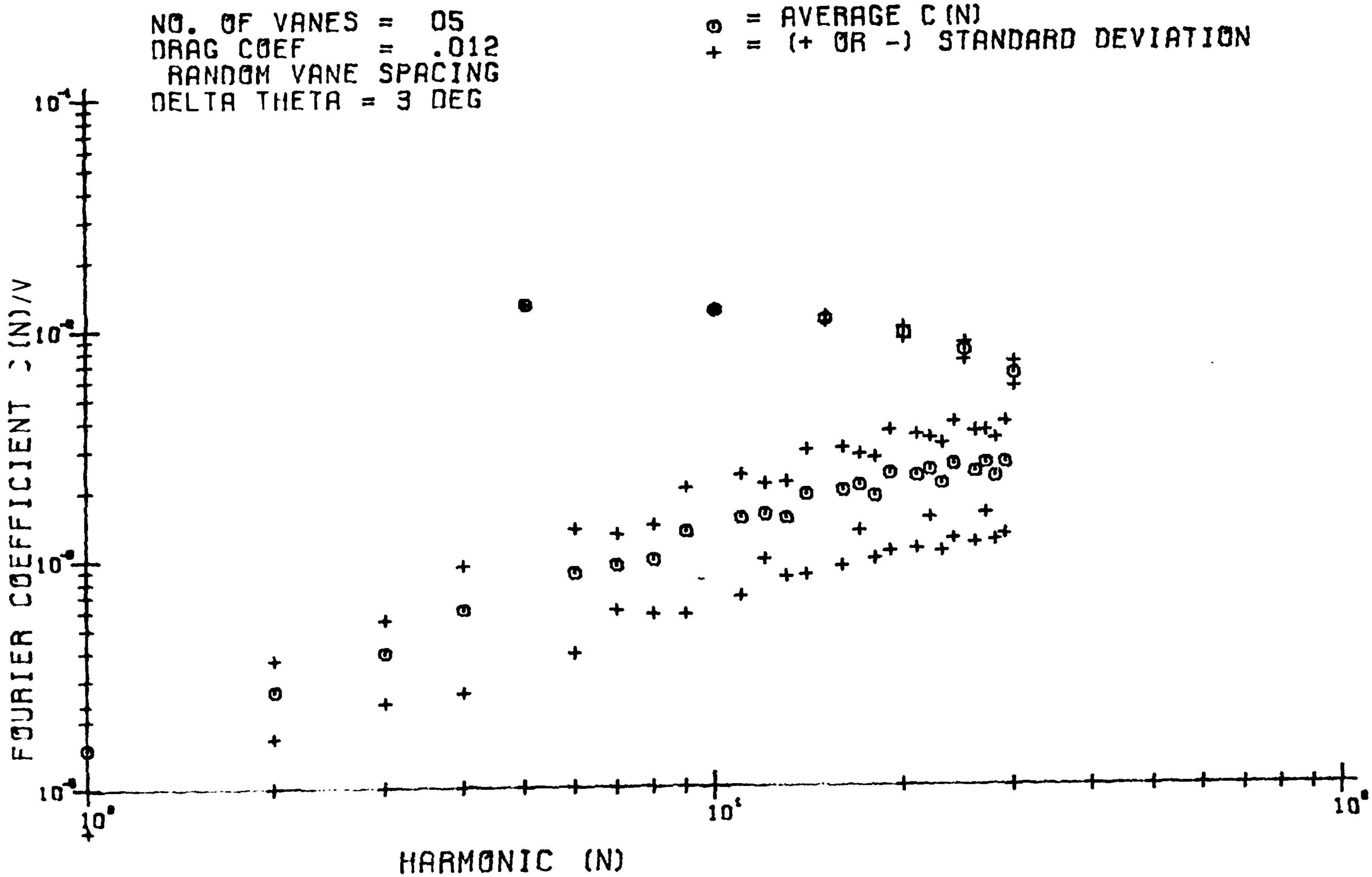


Figure 12. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 4.2%

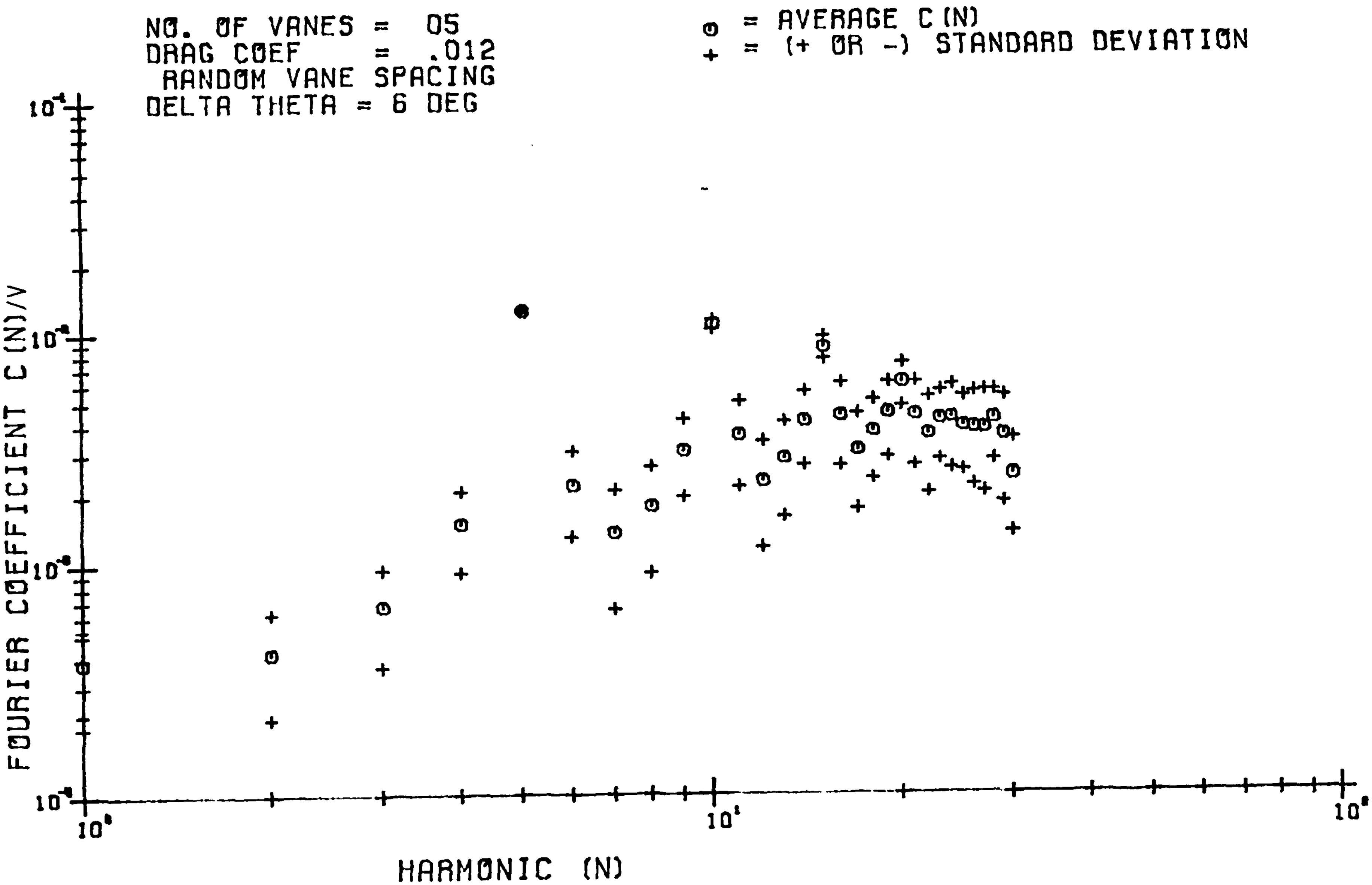


Figure 13. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 8.3%

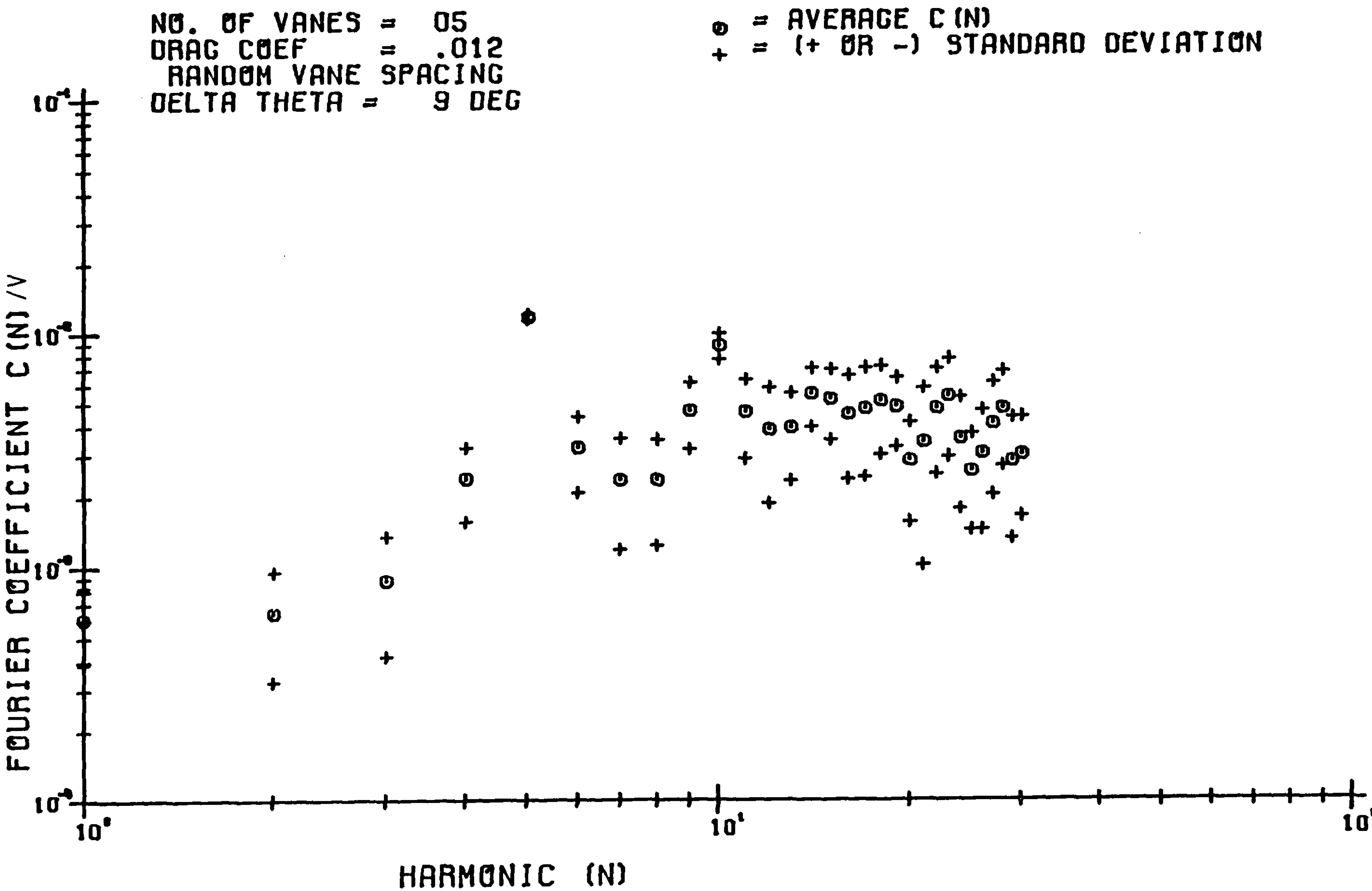


Figure 14. The Effect of Unevenly Spaced IGV on Fourier Amplitudes, Deviation = 12.5%

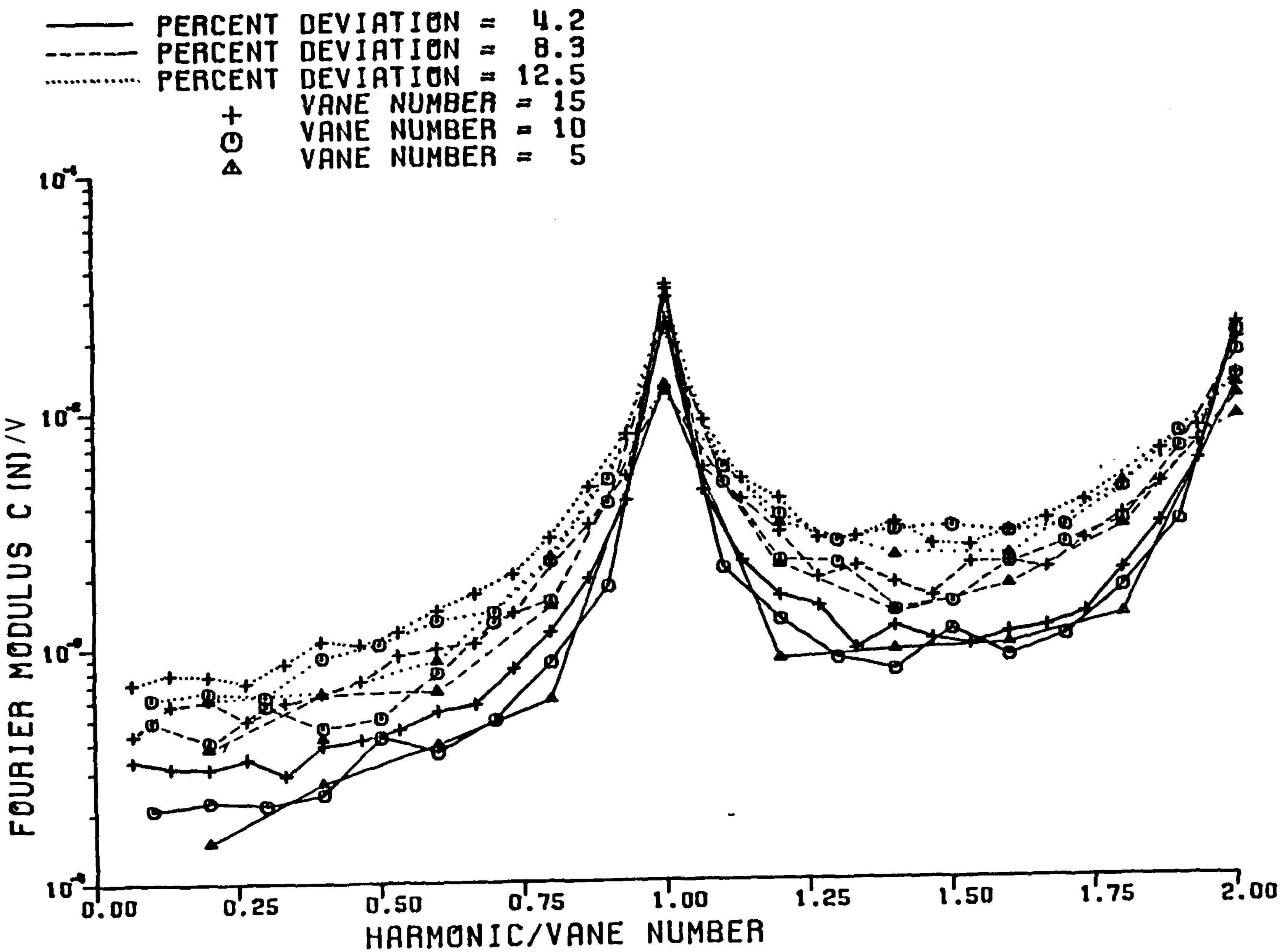


Figure 15. Fourier Amplitudes at Relative Harmonics of IGV With Varying Percent Deviation

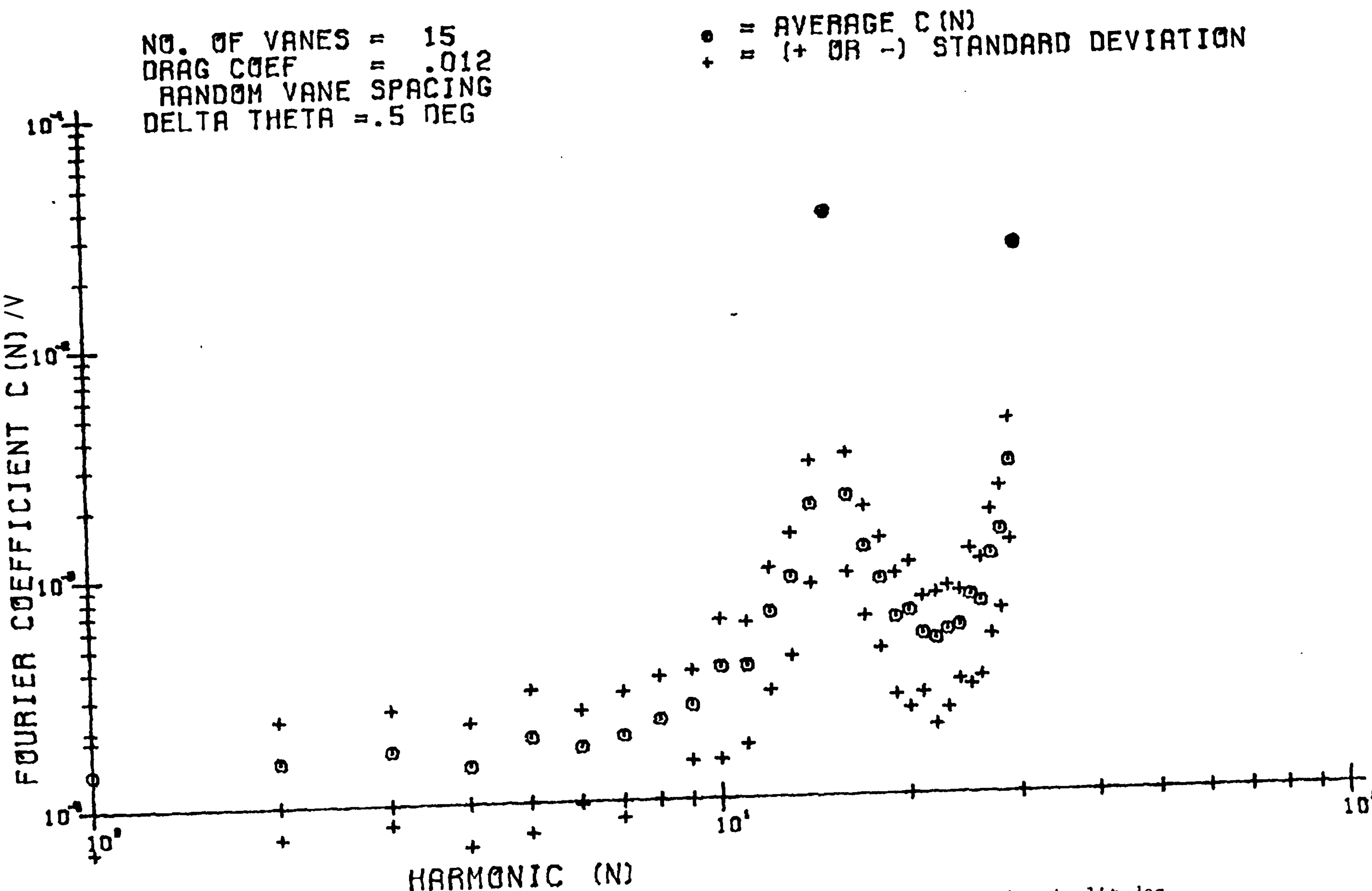


Figure 16. The Effect of Manufacturing Tolerances on Fourier Amplitudes

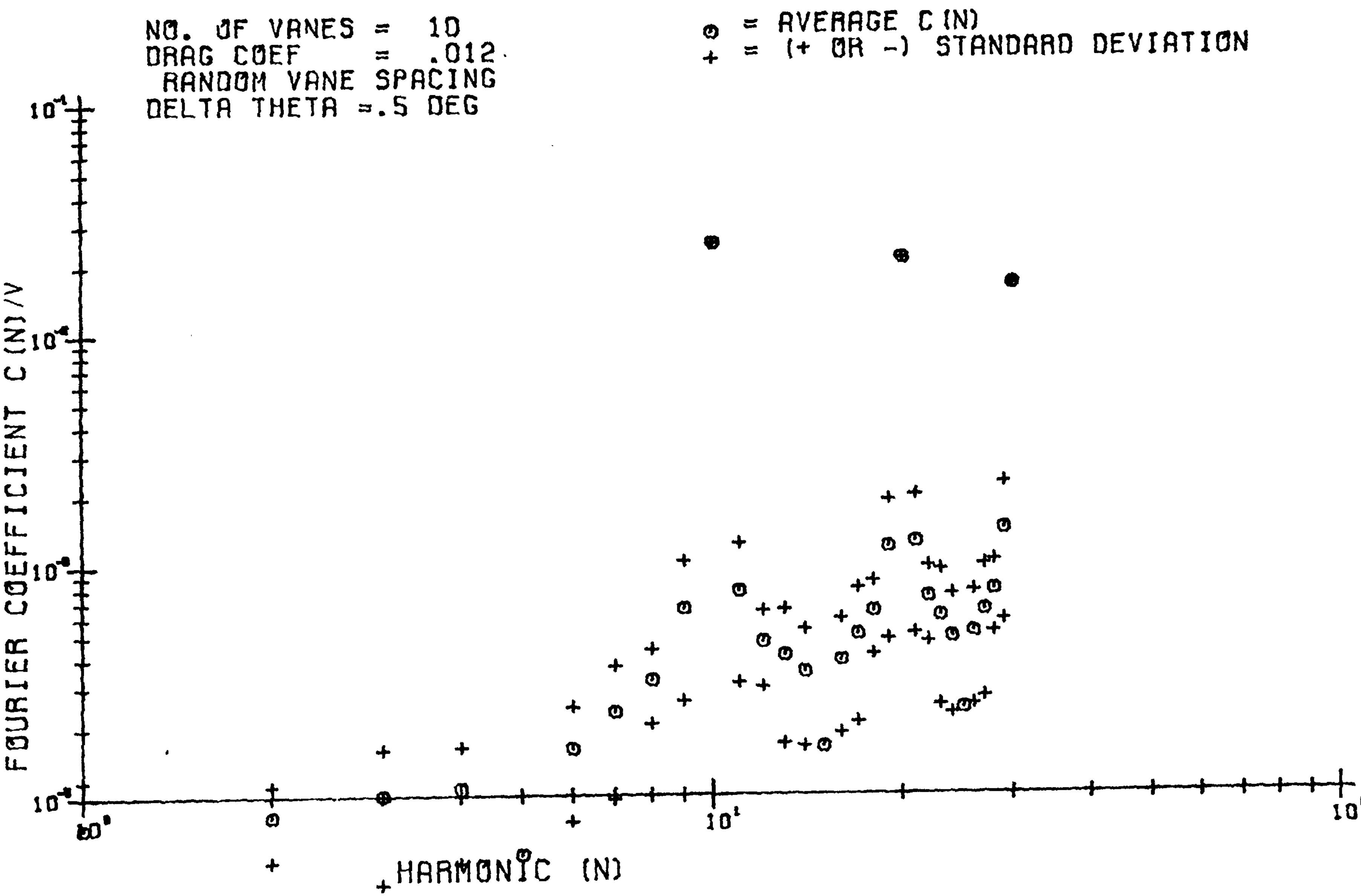


Figure 17. The Effect of Manufacturing Tolerances on Fourier Amplitude

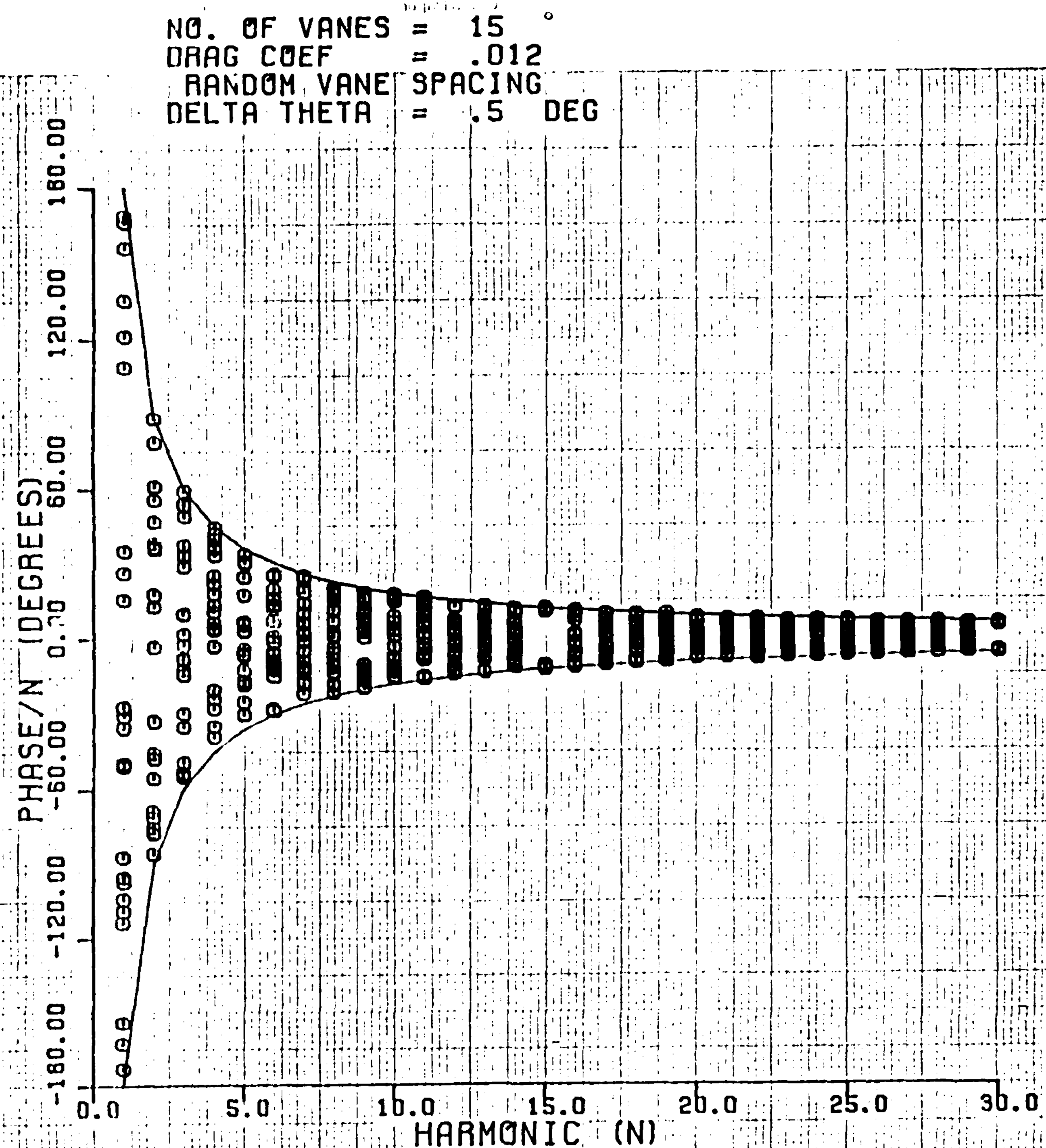


Figure 18. The Effect of Unevenly Spaced IGV on Fourier Phase Angles

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