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VORTEX GENERATOR DESIGN FOR AIRCRAFT INLET DISTORTION AS A NUMERICAL OPTIMIZATION PROBLEM

by

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INTRODUCTION

Aerodynamic compatibility of aircraft/inlet/engine systems is a difficult design problem for aircraft that must operate in many different flight regimes. Take-off, subsonic cruise, supersonic cruise, transonic maneuvering and high altitude loiter each place different constraints on inlet design. Vortex generators, small wing-like sections mounted on the inside surfaces of the inlet duct, are used to control flow separation and engine face distortion. This paper attempts to define the design of vortex generator installations in an inlet as a problem addressable by numerical optimization techniques. A performance parameter is suggested to account for both inlet distortion and total pressure loss at a series of design flight conditions. The resulting optimization problem is difficult since some of the design parameters take on integer values. If numerical procedures could be used to reduce multi-million dollar development test programs to a small set of verification tests, numerical optimization could have a significant impact on both cost and elapsed time to design new aircraft.

Inlet flow distortion is one of the most troublesome and least understood problems for designers of modern inlet engine systems (Refs. 1 and 2). One issue is that there are numerous sources of flow field distortion that are ingested by the inlet or are generated within the inlet duct itself. Among these sources are (a) flow separation at the cowl lip during maneuvering flight, (b) flow separation on compression surfaces due to shock-wave boundary layer interactions, (c) spillage of fuselage boundary layer into the inlet duct, (d) ingestion of aircraft vortices and wakes emanating from upstream disturbances, and (e) secondary flow and flow separation within the inlet duct itself. Most developing aircraft have experienced one or more of these types of problems, particularly at high Mach numbers and/or extreme maneuver conditions, such that flow distortion at the engine face exceeded allowable limits. Such compatibility problems were encountered in the early versions of the B70, the F-111, the F-14, the MIG-25, the Tornado and the Airbus A300, to name a few examples.

The effect of inlet distortion, be it pressure or temperature, steady or transient, is that the power available is reduced along the engine compressor surge margin (i.e. the difference between the operating line and the surge line). Aeromechanical effects such as rotor-blade forced response and distortion effects on flutter boundaries have received less attention, so that a consensus on importance and state-of-the-art methodology has yet to emerge. Stability characteristics of current high performance turbofan engines are adversely affected by both spatial as well as temporal distortion.

PROBLEM DEFINITION

One of the most commonly used methods to control local boundary layer separation is with the placement of vortex generators upstream of the problem area. Vortex generators in use today are small wing sections mounted on the inside surface of the inlet duct or wing surface, inclined at an angle to the oncoming flow to generate a shed vortex. The generators are usually sized to local boundary layer height to allow for the best interaction between the shed vortex and boundary layer itself, and are usually place in groups of two or more upstream of the problem area. The principle of boundary layer control by vortex generators relies on induced mixing between the external or core stream and the boundary layer region. This mixing is promoted by vortices trailing longitudinally over the duct surface adjacent to the edge of the boundary layer. Fluid particles with high momentum in the streamwise direction are swept along helical paths toward the duct surface to energize, and to some extent to replace, the low momentum boundary layer flow. This is a continuous process that provides a source of re-energization to counter the natural boundary layer growth caused by friction, adverse pressure gradients, and low energy secondary flow accumulation.

There are two basic configurations of vortex generators. In one configuration, all the vortex generators are inclined at the same angle with respect to the oncoming flow direction. These are called co-rotating configurations because the shed vortices rotate in the same direction. In the other configuration, the vortex generators are grouped in pairs one at a positive angle of attack and one at a negative angle of attack, such that pairs of counter-rotating shed vortices are generated. Co-rotating vortex generators are very effective in reducing flow separation if the generators are properly selected and located. The main advantage of co-rotating type vortex generators is their downstream effectiveness resulting in more effective usage of the vortex energy within the affected boundary layer. This type of vortex generator has a few special advantages when used within S-duct inlet configurations, namely: (1) the induced vortices will remain close to the wall resulting in a "cleaner" core flow, and (2) the induced vortices will counteract the natural and often strong secondary flow which develops.

Counter-rotating, equal strength vortex generators have been used in a number of aircraft inlet ducts, such as the F/A-18 and the center inlet duct on the production 727 aircraft. This type of vortex generator is very effective in reducing flow separation if the vortex generators are placed slightly upstream of the region of separation. The disadvantages of these types of generators, as compared to co-rotating generators, are: (1) the induced vortices tend to lift off the duct surface, thus reducing their effectiveness, (2) higher loss in inlet total pressure recovery, and (3) higher total pressure distortion at the compressor face.

It was not until the confirmation test for the refanned JT3D engine on the 727 center duct inlet in 1973 by Kaldschmidt, Syltebo, and Ting, Ref. 3, that an attempt was made to use vortex generators to restructure the development of secondary flow in order to improve the engine face distortion level. Thus, a very important shift in strategy on the use of vortex generators had occurred. The perspective had moved from a local two-dimensional boundary layer approach aimed at eliminating local flow separation to a global three-dimensional vortex-secondary flow

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interaction concept, where the design goal was now to control the development of three-dimensional secondary flow itself, by introducing discrete sources of vorticity at selected locations throughout the inlet duct.

In order to accomplish this new objective for internal flow control, the design strategy must shift from an experimental based methodology to an approach based on analysis. This paper represents one in a series of studies on the design issues associated with inlet-engine compatibility problems, and in particular, engine face distortion and its control. These studies center on the development of CFD tools and techniques which look promising within an analysis-design environment, and the application of these new analysis approaches to understand and control inlet-engine distortion. The first paper in this series by Anderson (Ref. 4) deals with the aerodynamic characteristics of vortex interaction within the F/A-18 inlet duct, where the vortex interaction arises as a result of a vortex ingestion. Later studies will involve the effect of vortex ingestion on the engine face flow field itself. In the second paper in this series, by Anderson and Levy (Ref. 5), it was demonstrated that an installation of co-rotating vortex generators could be constructed to tailor the development of secondary flow to reduce engine face distortion. Of importance is the conclusion that there exists an optimum axial location for the installation of co-rotating vortex generators, and within this configuration there exists a maximum spacing of generators above which the engine face distortion rapidly increases. This study also showed that the vortex strength, generator scale, and secondary flow field structure have a complicated and interrelated influence on the engine face distortion, over and above the influence of the initial arrangement of generators. These are the only three-dimensional calculations of inlets with vortex generators known to the authors.

ANALYSIS

With these computational tools in place the present paper attempts to pose the design of low distortion inlets through the use of vortex generators as a numerical optimization problem. To be a valid optimization problem a quantitative measure of goodness must be defined. Although inlet distortion is caused in the inlet, its effect is meaningful in the response of the engine to the distorted airflow. Inlet distortion can reduce surge margin and limit aircraft maneuverability. Aircraft and engine manufacturers have developed measures of inlet distortions that characterize the inlet flow, although they must be recalibrated for each airframe, engine and flight profile.

It is impractical to measure anything at the engine face when the engine is installed and operating; consequently, the engine and inlet designers agreed upon an Aerodynamic Interface Plane which is forward of the compressor face but sufficiently close to the engine face to have a similar flow field. Current U.S. practice uses forty or forty-eight transducer probes arranged in eight rakes with five or six rings. The radius of each ring is set such that all probes are at the centroid of equal areas. All distortion descriptors, whether they quantify steady state or transient distortion conditions, are always calculated relative to the standard rake located at the Aerodynamic Interface Plane.

The most widespread quantitative distortion descriptor available in the literature, because of its use in the earliest measurements on inlet ducts in the late 1950's, is simply:

$$DT = [Pt_{max} - Pt_{min}] / Pt_{ave} \tag{1}$$

where Pt_{max} is the maximum rake total pressure, Pt_{min} is the minimum rake total pressure, and Pt_{ave} is the area weighted average rake total pressure. In experimental data reduction, it is assumed that both the static pressure and temperature are constant and steady across the Aerodynamic Interface Plane; thus both the velocity and Mach number can be considered functions only of total pressure and the distribution of this quantity is the only measurement that needs to be made. This parameter is always useful to determine for comparison purposes and to describe the 'general health' of inlet ducts irrespective of the type of power plant that may be used.

The effect of circumferential distortion on compressor surge margin is essentially to drop the maximum pressure ratio of a constant corrected speed line. One descriptor for circumferential distortion is from Rolls Royce and is defined as

$$DC_{theta} = [Pt_{ave} - Pt_{min}] / q_{ave} \tag{2}$$

where Pt_{ave} and q_{ave} are the average total and dynamic pressure at the engine face or aerodynamic interface plane and Pt_{min} is the minimum total pressure in any section of extent theta. Significant theta values can vary with engine design and commonly are 60°, 90° and 120°. For bypass engines, a circumferential distortion descriptor $DC_{theta\text{-}GG}$ is often used, where GG indicates that the index is taken over the area of the gas generator.

More advanced distortion descriptors, introduced in the late 1960's and 1970's, take into account the Dt distortion of each ring of total pressure measurements. Thus, the radial distortion Dt_r is defined as

$$Dt_r = [[Pt_{max} - Pt_{ave}] / Pt_{max}]\mathrm{ring} \tag{3}$$

where Pt_{ave} is the average total pressure for a given ring radius and Pt_{max} is the maximum local ring total pressure. The circumferential distortion Dt_{theta} is defined as:

$$Dt_{theta} = [[Pt_{ave} - Pt_{min}] / Pt_{ave}]\mathrm{ring} \tag{4}$$

where Pt_{min} is the lowest total pressure in any theta segment, usually 60° or 180° of arc for a given ring radius having an average ring total pressure Pt_{ave}.

Whatever distortion parameter is selected, there are a large number of design parameters to be optimized. Figures 1, 2 and 3 define many of the geometric parameters which may vary from vortex generator to vortex generator in a single inlet, although in this study all vortex generators in each inlet were of the same size, shape and spacing. The effects of several parameters on inlet distortion are now presented. Note in the following examples that the parameters are highly coupled, i.e. the Hessian matrix is not well approximated as a diagonal matrix.

Vortex Generator Design Parameters

The 727/JT8D-100 center inlet duct geometry was used for illustrative purposes in this study. Other inlets, such as in the F-18 aircraft [4] can have significantly different distortion characteristics and different responses of inlet distortion to variations in vortex generation design parameters. The computations were made at an inlet entrance Mach number of 0.6, and Reynolds numbers that ranged from 4.0×10^6 to 16.0×10^6 based on hydraulic inlet diameter (D_i), and inflow conditions that correspond to a shear layer thickness $\delta/D_i = 0.005$.

The geometry of the co-rotating vortex generators used in this study, along with the nomenclature used in positioning the individual blades are presented in Figs. 1, 2 and 3. The important geometric design parameters include: (1) the vortex generator blade height (h/R_i), (2) the blade chord length (c/R_i), and (3) the vane angle of attack (β_{vg}). For all the calculations within this study, the vortex generator blade height (h/R_i) was set at 0.075, the ratio of generator height to chord length (h/c) was fixed at 0.5, and the vane angle of attack (β_{vg}) was set at 16.0°. Instead of the usual spacing parameter (d/R_i), i.e., the distance between adjacent blades, the positioning of the vortex generator blades was described in terms of spacing angle (α_{vg}) and a sector angle over which the blades were positioned (θ_s).

Shown in Fig. 4 is the axial location of the vortex generator sector region (X_{vg}/R_i) covered in this study. These sector regions were located between $X_{vg}/R_i = 1.0$ and $X_{vg}/R_i = 7.0$, and cover a sector angle (θ_s) up to 157.5° as measured counter-clockwise relative to an azimuthal angle of 180° with respect to the vertical axis of the duct.

Installed Vortex Generator Performance Characteristics

The effect of Reynolds number on engine face peak 60°-sector circumferential pressure ring distortion is presented in Fig. 5 for the baseline inlet duct, i.e., without vortex generators. There is a significant increase in maximum circumferential pressure ring distortion, from 0.045 to 0.087, over the Reynolds number range from 16.0×10^6.

Presented in Fig. 6 is the influence of Reynolds number on engine face distortion for the vortex generator installation composed of 9 generators located at an axial location $X_{vg} = 5.0$. For this installation of vortex generators, the maximum 60°-sector circumferential pressure ring distortion index remains reasonably level between the Reynolds numbers of 16.0×10^6 and 8×10^6. For Reynolds numbers less than 8.0×10^6 the flow at the engine face "breaks" down and the distortion increases very rapidly. The systematic and continuous nature of the flow field breakdown can be seen in the engine face total pressure recovery maps presented in Fig. 5. Installed vortex generator performance, as measured by engine face circumferential distortion descriptors, is sensitive to Reynolds number and thereby the generator scale, i.e., the ratio of generator blade height to local boundary layer thickness. Installations of co-rotating vortex generators work well in terms of minimizing engine face distortion within a limited range of generator scales. This means that the design of vortex generator installation is a point design, and all other conditions are off-design.

The relative engine face distortion levels at different flight conditions is important since inlets must be designed to operate with low distortion over the flight envelop. Trades between what is needed at one flight condition, such as takeoff, and what is needed at other conditions, such as transonic maneuvering at low altitudes or cruise, must be made. Reynolds number, Mach number, inlet mass flow and engine tolerance to distortion can all change from one operating condition to another. The different shapes of curves in Figs. 4 and 5 represent different relationships between distortion levels at key aircraft operating conditions.

The relative engine face distortion at different flight conditions is important since inlets must be designed to operate with sufficiently low distortion at all critical flight conditions. Trade-offs between what is needed at one flight condition (e.g., take-off) and what is need at other flight conditions (e.g. transonic maneuvering at low altitudes or high Mach number cruise at high altitude) must be made. Reynolds number, Mach number, inlet mass flow and engine tolerance to distortion can all change from one operating point to another. The different shapes of curves in Figures 5 and 6 represent different relationships between distortion levels at key aircraft operating conditions.

Figures 7 and 8 show the change in distortion with the number of vortex generators. Vortex sector angle increases as the number of vortex generators is increased because of constant spacing between generators causing a decrease in engine face distortion. The vortex generators are at x/R = 3 in Figure 7 and at x/R = 5 in Figure 8 where the distortion levels are lower. The effect of axial location is shown in Figure 9 showing an optimum in this case at x/R between 5 and 6. The effect of spacing between vortex generators is shown in Figure 10 for a 127.5° sector angle at x/R = 5 indicates that generating strong vorticity at the correct location can significantly reduce distortion. Parameters such as vortex generator height, length and angle of attack have not yet been systematically studied in other than simple model problems.

NUMERICAL OPTIMIZATION PROBLEM

Design of complex systems by numerical optimization techniques is becoming an accepted, and in some cases even a standard approach. Vortex generator design for aircraft inlets can be cast in a form to bring the large body of optimization tools to bear on this problem. Comments will now be made on the choice of design variables, the performance parameters and requirements for a numerical optimization method.

The design variables include the geometric variables of each vortex generator, i.e., length, height, and geometric angle of attack. They also include the relationship between vortex generators such as their circumferential separation, α, and their axial location, x. These variables are continuous. However, the number of vortex generators used is also a design variable which must take integer values. In addition, the geometric angle of attack of a particular vortex generator has local optima at both positive and negative values. These correspond to the co-rotating and counter-rotating cases described above.

Selection of a performance parameter is a particularly difficult task for three reasons. First, the required distortion level can be different at each important flight condition. Second, distortions worse than the requirement are unacceptable whereas distortion levels better than the requirement are of limited value. Third, use of vortex generators can cause loss of total pressure which implies loss of thrust.

At each flight condition, i, a performance parameters could have the form:

$$P_i = f_p\left[D_i^* - D_i\right] * \left[\Delta P_i^0 \; g_i \; m_i^f\right] \qquad (5)$$

where D_i is the distortion at the flight condition, D_i^* is the allowed distortion, f_p is either a penalty function or a barrier function. As a penalty function it is adverse when the argument is negative and constant or only moderately improving when the argument is positive. As a barrier function it gets increasingly adverse as the argument approaches zero. ΔP_i^o is the pressure loss in the inlet including the effect of vortex generators, m_i^f is the rated fuel burned at this flight condition and g_i is the gross-to-net thrust ratio. This performance parameter sums the contribution of performance parameters at several flight conditions. The contribution from each flight condition is weighted by the amount of fuel burned in that segment of the flight by the second term in (5). Consequently this term heavily weights the design to good cruise performance. The first term in (5) requires that an acceptable level of distortion be achieved at all flight conditions. The barrier or penalty function must be designed to prohibit unacceptable distortion levels since this can result in engine damage or worse. The weighted summation of performance at each flight condition is analogous to techniques presently used for component design in aircraft systems. Using the discrete penalty function:

$$f_\delta(a) \quad \begin{cases} = 1 & a \geq 0 \\ = \infty & a < 0 \end{cases} \tag{6}$$

in Equation (5) results in a statement of the engineering problem that may preclude the use of differential methods.

Evaluation of the performance parameter for each set of design variables requires solution to a set of four partial differential equations at 250,000 to 500,000 node points. Each evaluation uses 6 to 12 minutes of CPU time on a Cray X-MP or Y-MP. At commercial Cray computer cost of $200 per hour, performance parameter evaluations are not excessively expensive compared to multi-million dollar model tests in a wind tunnel. Evaluation on an engineering workstation at 1/10 the Cray speed and a purchase price on the order of $15,000 allows a trade of evaluation cost versus time.

Two computational strategies are suggested. The first is based on gradient methods and uses the barrier function. First order "steepest descent" methods are not expected to be useful because of the strong interaction among the variables. In particular, consider terms of the form

$$\frac{\partial^2 P}{\partial x_i \partial x_j} \quad . \tag{7}$$

where x_i and x_j are design variables and P is the performance parameter. Successful solution by first order gradient techniques can be inhibited by large values of (7) for $i \neq j$ compared to terms where $i = j$. In these cases higher order methods are required. A full second order method requires many evaluations of the performance parameter, which can be costly. Quasi-Newton techniques approximate the matrix terms, Eq. (7), by a positive definite matrix. The approximation improves with successive 1-D searches.

Since the number of vortex generators is not a continuous variable and since co-rotating and counter-rotating vortex generators form two classes of solutions, a series of optimization problems need to be solved. The most favorable of the separate cases would be selected as the favored design.

Rather than solve the entire problem *de novo*, aspects of a design could be improved by numerical optimization strategies. For example, vortex generator height, length and angle of attack could be held constant. Then for a predetermined number of co-rotating vortex generators, their location and spacing could be optimized using traditional optimization techniques.

A second strategy is discrete and uses the discrete penalty function, Eq. (6). The resulting optimization problem is a mixed discrete-continuous design variable problem with a discontinuous performance parameter. Discrete optimization techniques, such as simulated annealing, may be adapted to this hybrid problem. Such techniques can require a large number of evaluations of the performance parameter, so careful strategies must be adopted. Such strategies are areas for further research.

CONCLUSIONS

Vortex generator design for aircraft inlets has played an important role in solving inlet distortion problems in the last 20 years. Present design procedures are based on expensive and therefore limited model tests. With the ability to compute inlet flows with vortex generators comes the ability to apply numerical optimization techniques to the design problem, at least in a limited sense.

A performance parameter is suggested to account for both inlet distortion and total pressure loss at a series of design flight conditions. The resulting optimization problem is difficult since some of the design parameters take on integer values. If numerical procedures could be used to reduce development test programs to a small set of verification tests, numerical optimization could have a significant impact on both cost and elapsed time to design new aircraft.

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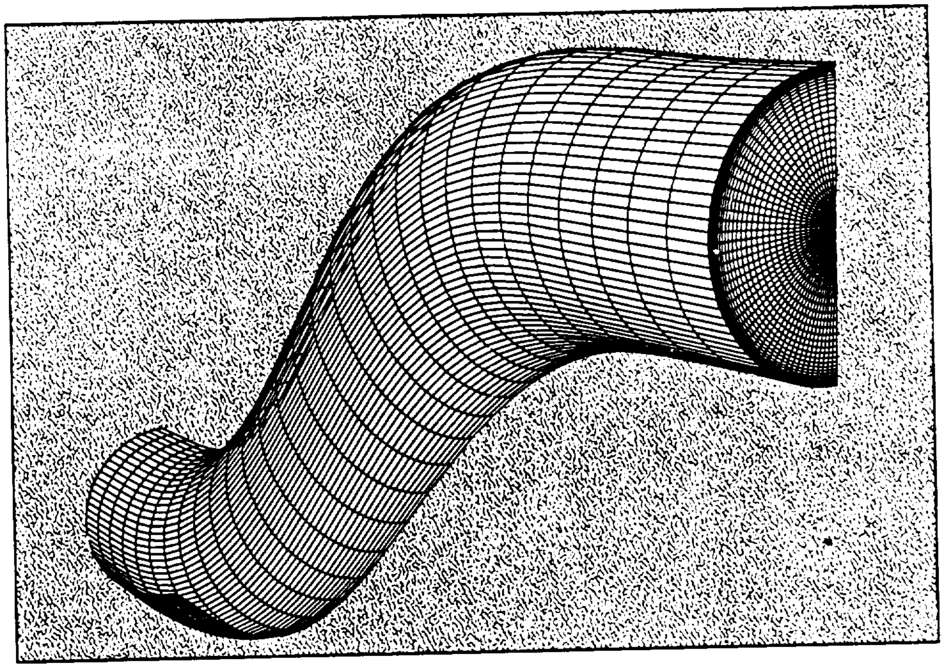

Figure (1) - Geometry definition for the 727/JT8D-100 center inlet.

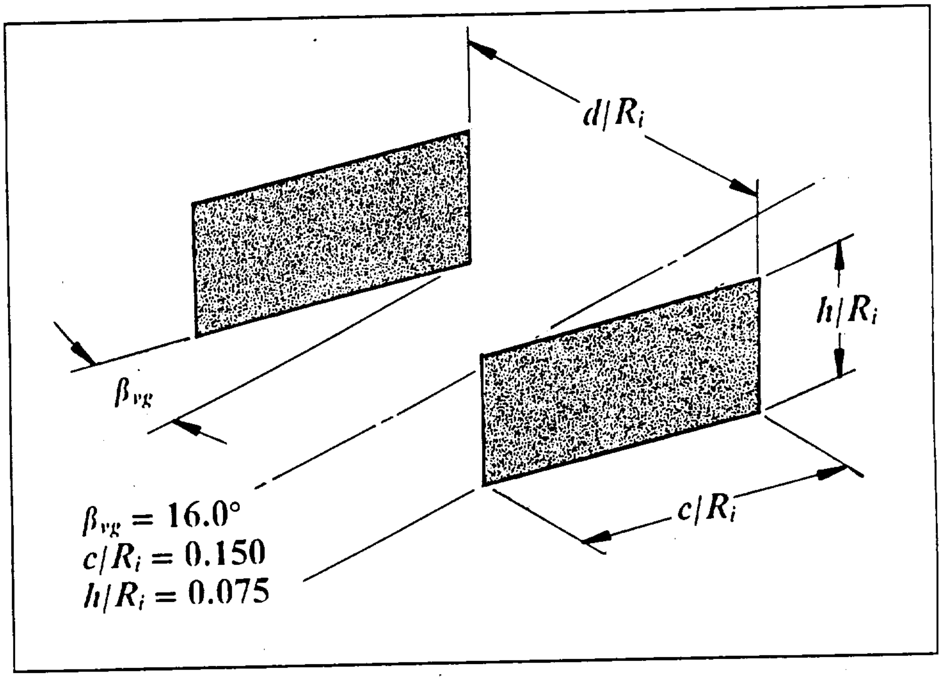

Figure (2) - Geometry definition of co-rotating vortex generators.

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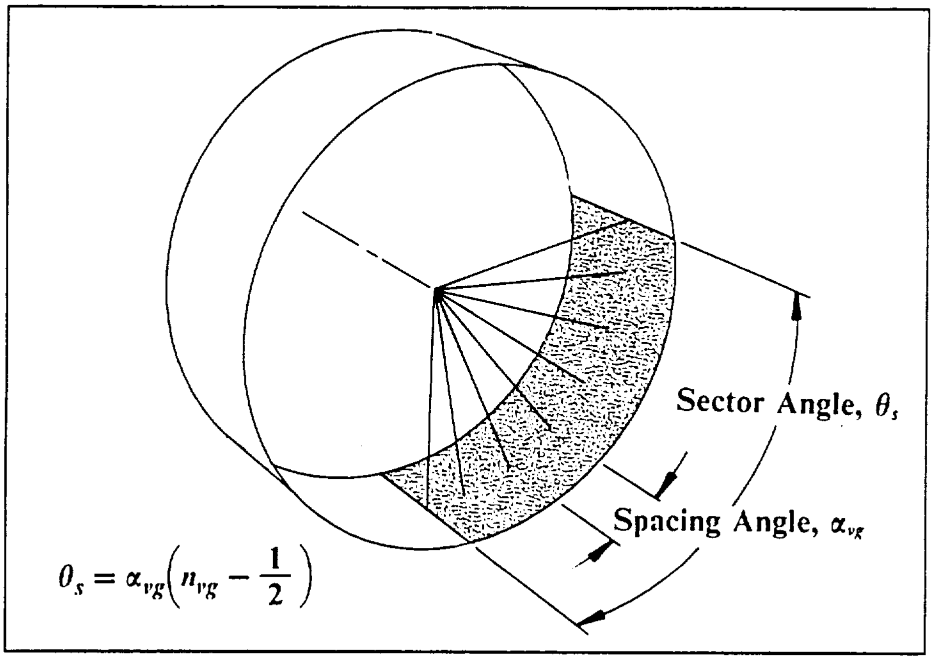

Figure (3) - Nomenclature used for vortex generator positioning.

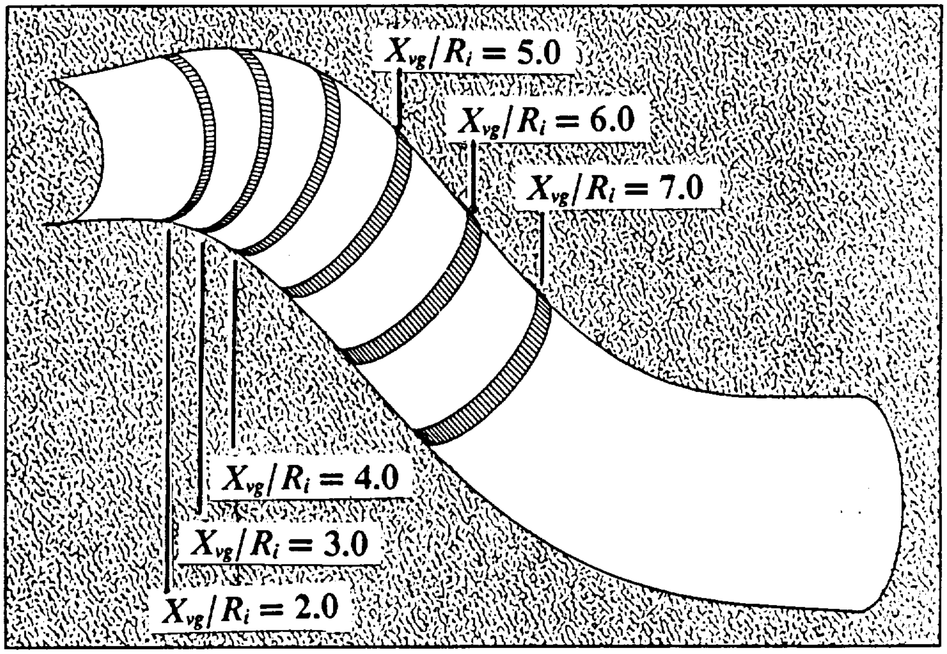

Figure (4) - Axial locations of the vortex generator sector regions.

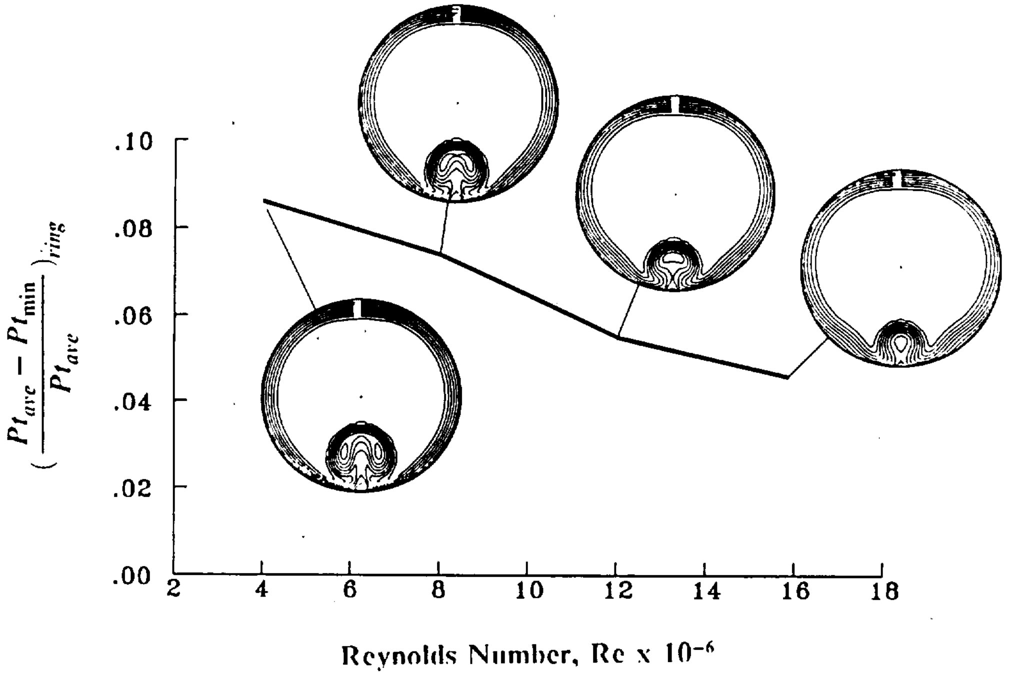

Figure (5) - Effect of Reynolds number on the maximum 60°-sector circumferential pressure ring distortion without vortex flow control.

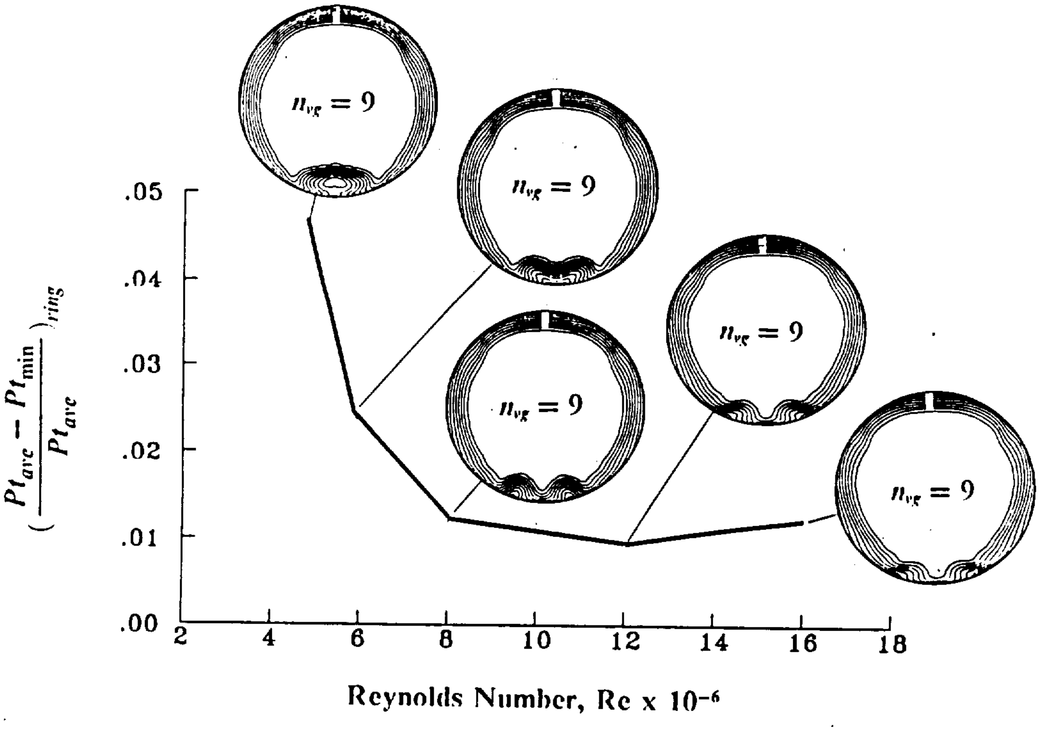

Figure (6) - Effect of Reynolds number on the maximum 60°-sector circumferential pressure ring distortion at $X_{vg}/R_i = 5.0$

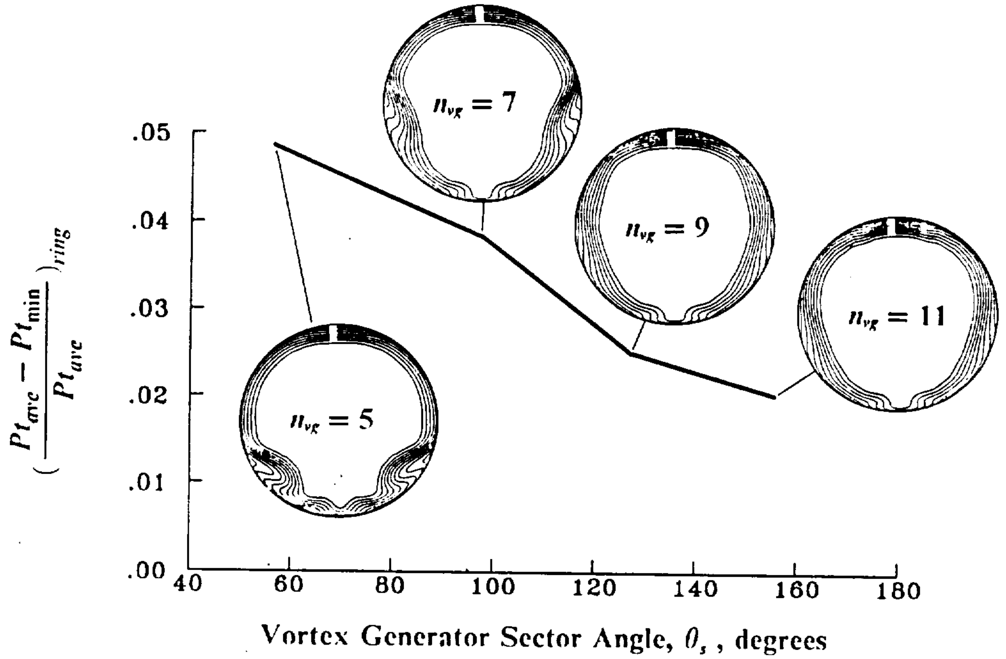

Figure (7) - Effect of vortex generator sector angle (θ_s) on the maximum 60°-sector circumferential pressure ring distortion at $X_{vg}/R_i = 3.0$.

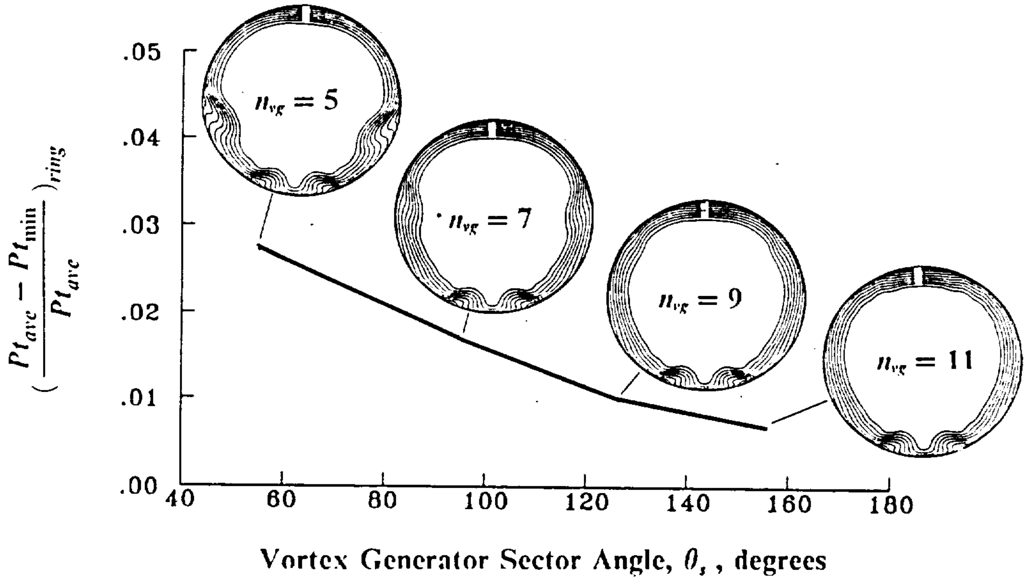

Figure (8) - Effect of vortex generator sector angle (θ_s) on the maximum 60°-sector circumferential pressure ring distortion at $X_{vg}/R_i = 5.0$.

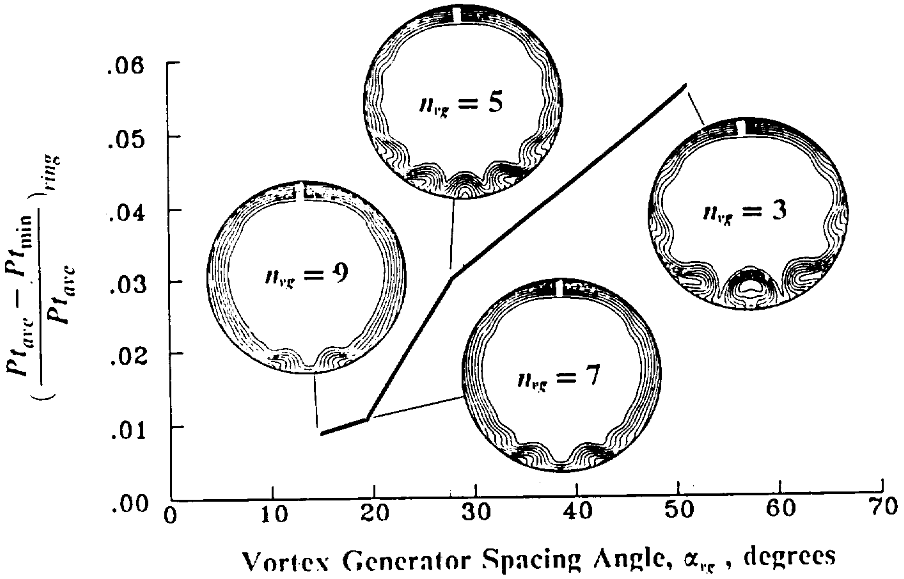

Figure (9) - Effect of vortex generator spacing angle (α_{vg}) on the maximum 60°-sector circumferential pressure ring distortion.

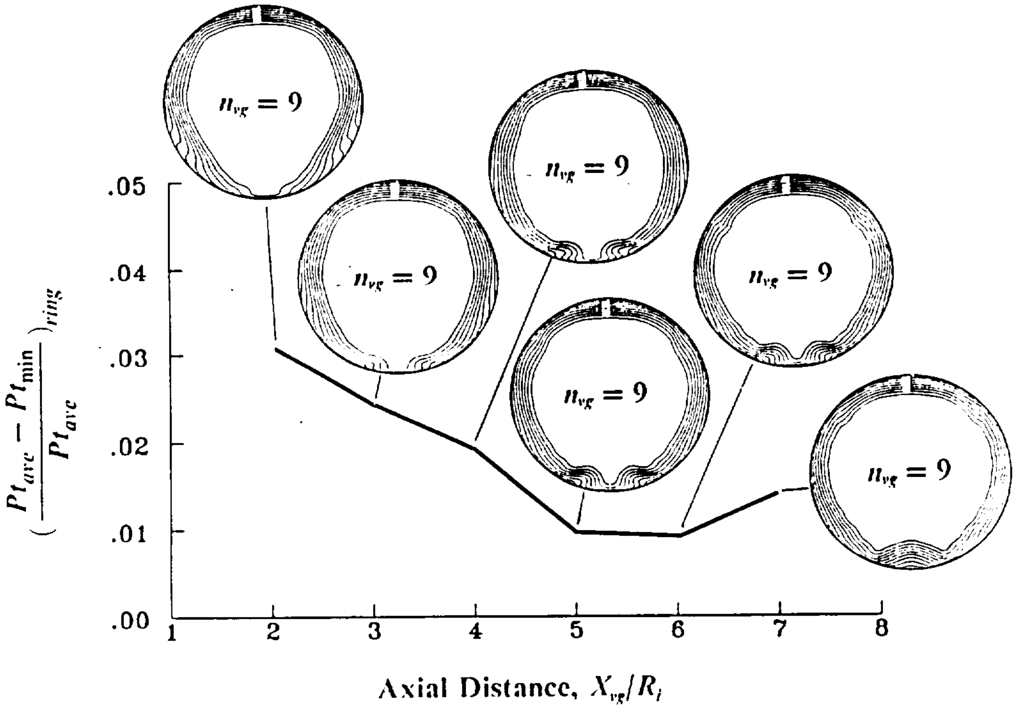

Figure (10) - Effect of vortex generator sector location (X_{vg}/R_i) on the maximum 60°-sector circumferential pressure ring distortion.