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ABSTRACT

The dynamic characteristics of an engine blade are evaluated under pre-and-post ice impact conditions using the NASA in-house computer code BLASIM. The ice impacts the leading edge of the blade causing severe local damage. The local structural response of the blade due to the ice impact is predicted via a transient response analysis by modeling only a local patch around the impact region. After ice impact, the global geometry of the blade is updated using deformations of the local patch and a free vibration analysis is performed. The effects of ice impact location, ice size and ice velocity on the blade mode shapes and natural frequencies are investigated. The results indicate that basic nature of the mode shapes remains unchanged after impact and that the maximum variation in natural frequencies occurs for the twisting mode of the blade.

NOMENCLATURE

SYMBOL

E	elastic modulus (psi)
$\{F\}$	force vector
G	shear modulus (psi)
$[K]$	stiffness matrix
T	kinetic energy
$[M]$	mass matrix
n	total number of degrees of freedom
S_T	tensile strength (psi)
S_c	compressive strength (psi)
S_s	shear strength (psi)
$\{U\}$	amplitude vector of n degrees of freedom
$\{\dot{U}\}$	velocity vector of n degrees of freedom
ρ	density ($lbf.sec^2/in^4$)
ν	Poisson's ratio
ω	natural frequency (cycles/sec)

SUBSCRIPT

a	analysis degrees-of-freedom
o	omitted degrees-of-freedom
r	reduced matrix

SUPERSCRIPT

-1	inverse matrix
T	transpose matrix

INTRODUCTION

At high altitude, when an aircraft travels through clouds of super-cooled water droplets or regions of rain, water particles attached to the engine inlet edges undergo a phase change and become ice. With time, the ice accretes on the inlet and sheds due to the structural vibration of the aircraft and impacts the blade (Figure 1). The ice impact velocity relative to the blade is very large and hence can cause severe local deformations. Consequently, these deformations may alter the blade geometry and its dynamic characteristics significantly. This may cause degradation of engine performance and subsequently may lead to a catastrophic failure of the blade and the engine. Hence, it is necessary to study the dynamic characteristics of the blade under pre-and-post ice impact conditions.

The objective of this paper is to study the effect of ice impact on the dynamic characteristics of the blade. Efforts have been underway at NASA Lewis Research Center to develop a computer code, BLASIM (BLades ASsessment for Ice iMpact) [1] to assess the damage caused by ice impact locally [2] and at the root [3]. BLASIM can be used to perform static, dynamic, fatigue, and flutter analyses of fan blades. Recently, the code has been enhanced to simulate identical sequential ice impact on the same blade with geometry update of the blade after each impact. The change in the dynamic characteristics of the blade due to the first ice impact as well as the effect of ice impact location, ice size and ice velocity are investigated.

ANALYSIS

Blade Modeling

In BLASIM, the blade can be defined using one of two options: (1) specify a maximum of 21 airfoil stations with their coordinates, blade radius and stagger angle at each station or (2) input a total of 55 nodal grid points and thicknesses (Figure 2). The blade is then modeled using 80 triangular plate finite elements similar to the NASTRAN TRIA3 element [4]. The TRIA3 element is a reduced integration triangular plate bending element of the QUAD4 family. Some of the features of this element are: recognition of thickness taper, meshing that simulates airfoil pretwist and camber, composite material capabilities. Each nodal grid point has six degrees of freedom: three translational and three rotational.

Ice Impact Analytical Model

The piece of ice which impacts the blade is modeled as a spherical object. The ice impacts the blade at the leading edge with a velocity equivalent to that of the aircraft. A schematic depicting the geometry of a piece of ice impacting the blade is shown in Figure 3a. The angle θ at which ice impacts the blade is a function of the ice velocity and the engine speed. The magnitude of the force resulting from the impact is a function of both the impact angle and the mass of the ice piece. As shown in Figure 3b, if the diameter of the piece of ice is larger than the spacing between two adjacent blades, only a part of the piece of ice impacts the blade. The factors affecting the structural response of the blade subjected to ice impact are the mass of the ice piece, ice velocity, blade size, location of impact and engine speed.

Ice impact occurs on the leading edge of the blade. Since the damage caused by the impact is highly localized, only a portion of the blade around the impact region (i.e., a specified local patch along the span and half of the blade along the chord as shown in Figure 4) is modeled. The impact region is defined with two parameters, namely, lower and upper bounds of radial fractions, a and b. The impact force is loaded at the specified mid-node of the local patch model along the leading edge of the blade. The impact region is modeled using 35 nodes and 48 elements. A total of 16 elements surrounding the impact node are assumed to be fully stressed and undergo large deflection. The stiffness of these elements are modified to reflect the perfectly plastic condition.

Modal integration technique is used to obtain the undamped transient response of the local ice impact region. Only the first five modes of the local patch are included in the analysis. Details on the theoretical formulation employed in BLASIM for the local ice impact analysis are discussed in Reference [2].

Blade Geometry Update

The identical sequential ice impact option updates the blade geometry following each impact. The logical flow of the update process is described in Figure 5. The local patch impact displacements are transformed to global nodes of the finite element grid using a linear numerical interpolation scheme. Once the global blade geometry has been updated, a free vibration analysis is performed for the entire blade. This process can be repeated a prescribed number of times to simulate identical sequential impact. In this paper, analysis is carried out only before and after the first ice impact.

Dynamic Analysis

The dynamic characteristics of the blade can be obtained by solving the eigenvalue problem for the free vibration analysis of the undamped system using

$$\left([K] - \omega^2[M]\right)\{U\} = \{0\} \tag{1}$$

where $\{U\}$ is the amplitude vector of n degrees of freedom at the nodes and is called modal vector, $[K]$ is the stiffness matrix, $[M]$ is the mass matrix and ω is the natural frequency.

BLASIM employs the Guyan reduction procedure [5] to reduce the number of degrees of freedom of the structure without compromising the numerical accuracy. It results in a smaller set of equations for the dynamic analysis and leads to greater computational efficiency.

For the static analysis of the structure, the equilibrium equation of the finite element model can be expressed as

$$\begin{bmatrix} K_{aa} & K_{ao} \\ K_{oa} & K_{oo} \end{bmatrix} \begin{Bmatrix} U_a \\ U_o \end{Bmatrix} = \begin{Bmatrix} F_a \\ F_o \end{Bmatrix} \tag{2}$$

where $[K_{aa}]$, $[K_{ao}]$, $[K_{oa}]$ and $[K_{oo}]$ are the submatrices of the stiffness matrix $[K]$, $\{U_a\}$ and $\{U_o\}$ are the subvectors of the modal vector $\{U\}$, and $\{F_a\}$ and $\{F_o\}$ are the subvectors of the force vector $\{F\}$. The subscripts a and o refer to the analysis and omitted degrees of freedom, respectively.

Neglecting $\{F_o\}$ in Equation (2), the solution for $\{U_o\}$ is defined by

$$\{U_o\} = [H_{oa}]\{U_a\} \tag{3}$$

where

$$[H_{oa}] = -[K_{oo}]^{-1}[K_{oa}] \tag{4}$$

Eliminating $\{U_o\}$ in Equation (2), the stiffness matrix reduces to

$$[K_r] = [K_{aa}] + [K_{ao}][H_{oa}] \tag{5}$$

where subscript r refers to the reduced stiffness.

Equating the kinetic energies before and after the reduction leads to

$$\frac{1}{2}\{\dot{U}\}^T[M]\{\dot{U}\} = \frac{1}{2}\{\dot{U}_a\}^T[M_r]\{\dot{U}_a\} \tag{6}$$

where $\{\dot{U}\}$ is the velocity vector.

The kinetic energy T can be written as

$$T = \begin{Bmatrix} \dot{U}_a \\ \dot{U}_o \end{Bmatrix}^T \begin{bmatrix} M_{aa} & M_{ao} \\ M_{oa} & M_{oo} \end{bmatrix} \begin{Bmatrix} \dot{U}_a \\ \dot{U}_o \end{Bmatrix} \tag{7}$$

Substituting for $\{\dot{U}\}$ and expanding Equation (7)

$$T = \frac{1}{2}\{\dot{U}_a\}^T[\,[M_{aa}] + [M_{ao}][H_{oa}] + [H_{oa}]^T([M_{oa}] + [M_{oo}][H_{oa}]\,)]\{\dot{U}_a\} \tag{8}$$

From Equation (8), the reduced mass matrix can be identified as

$$[M_r] = [M_{aa}] + [M_{ao}][H_{oa}] + [H_{oa}]^T([M_{oa}] + [M_{oo}][H_{oa}]\,) \tag{9}$$

For a general blade, the predominant degrees-of-freedom at the tip are those in the normal, tangential and radial directions (i.e, translational degrees-of-freedom only). In the code, the degrees of freedom included in the analysis set are shown in Figure 2. The six nodes with open circles correspond to the normal degrees-of-freedom and the six nodes with solid circles correspond to the normal, tangential and radial degrees-of-freedom. The centrifugal stiffening effects due to rotation are included in the stiffness matrix via a differential stiffness approach [6].

RESULTS AND DISCUSSION

In this paper, a modified SR-2 titanium unswept propfan blade [7] is considered for the dynamic analysis. The blade finite element model is shown in Figure 2. The setting angle of the blade (orientation of the blade chord with respect to the plane of rotation) at 75% of the span is 57° and the number of blades is 8. The material properties used in the analysis of the titanium blade are $E = 16.5\text{x}10^6$ psi, $G = 6.4\text{x}10^6$ psi, $\nu = 0.3$, $\rho = 0.000444$ lbf.sec^2/in^4, $S_T = S_C = 7.4\text{x}10^4$ psi and $S_S = 4.4\text{x}10^4$ psi. The engine speed considered is 4000 RPM. The dynamic characteristics of the blade are compared before and after first ice impact.

Effect of Ice Impact Location

The natural mode shapes and frequencies of the SR-2 blade are evaluated before and after first ice impact for a number of impact locations along the span. A piece of ice with a radius of 0.8" and travelling at a velocity of 120 knots is considered to be impacting the leading edge of the blade. The pre-impact natural mode shapes of the SR-2 blade are shown in Figure 6a. The first two natural modes indicate that the blade is undergoing pure bending while the third one corresponds to a twisting mode. The bending modes are similar to the first two modes of a cantilever beam.

A dynamic analysis of the blade is carried out after the ice impacts the blade at an impact location varying from 40 to 90% of the span. The deformed blade and its natural mode shapes at three impact locations: 69, 80 and 89% of the span are shown in Figures 6b-6d . In order to have a better 3-D visual effect of the blade modal deformation, modal displacements at the finite element nodes are interpolated and a denser mesh is shown in these Figures. In all three cases, it can be seen that the basic nature of the first three modes remains the same after first impact, except that the impact deformations are reflected in the mode shapes.

The variation of natural frequencies with impact location is shown in Figure 7. The first two natural frequencies increased after impact because of an increase in the convexity that resists the bending deformation of the blade. The maximum increase in the first and second frequencies were 2.3% and 8% at impact locations of 69% and 80% of the span, respectively. However, the third frequency decreased after impact about 19% at an impact location of 69%. This decrease is caused by a reduction in the chordwise stiffness of the blade associated with the twisting mode. The stiffness contribution from the portion of the blade near the tip towards the overall stiffness is very small. Hence, the variation in the dynamic characteristics due to ice impact becomes less significant as the impact location moves toward the blade tip.

Effect of Ice Size

The effect of ice size on the variation in the dynamic characteristics of the SR-2 blade due to ice impact is shown in Figures 8a-8c. Ice impact analysis is performed varying the ice size from 0.1" to 0.8" with ice impact location as a parameter (69%, 80% and 89% of the span). It can be seen that the third frequency experiences the largest variation after ice impact. This maximum change occurred at an ice radius of 0.5" with an impact location of 80% of the span where the frequency decreased about 20.5%. The results indicate that there exist an ice radius for which the change in frequency due to ice impact is maximum. It can be seen that the third frequency experiences the largest variation due to ice impact.

Effect of Ice Velocity

Figures 9a-9c show the effect of ice velocity on the variation in the dynamic characteristics of the SR-2 blade. Ice impact analysis analysis is performed varying the ice velocity from 10 to 280 knots with ice impact location as a parameter (69%, 80% and 89% of the span). The third mode undergoes the maximum change in frequency due to impact at 69% of the span. The decrease is 19% at an ice velocity of 100 knots. The results show that there exist an ice velocity for which the change in frequency due to ice impact is maximum.

CONCLUSIONS

BLASIM, a NASA LeRC in-house, stand-alone, portable and documented computer code, is used to evaluate the dynamic characteristics of a blade under pre-and-post ice impact conditions. The following conclusions can be drawn from the results presented here:

1. The natural frequencies, especially the third mode, are significantly altered after first ice impact (≈21%).
2. The natural frequency that corresponds to twisting experiences a maximum change due to ice impact than those corresponding to bending modes.
3. The basic nature of the first three modes remains the same after first impact, except that the impact deformations are reflected in the mode shapes.
4. The change in the dynamic characteristics of the blade caused by ice impact becomes less significant as the impact location approaches the blade tip.
5. For a given blade and ice impact location, there exist an ice radius and velocity that correspond to maximum change in the blade natural frequencies.

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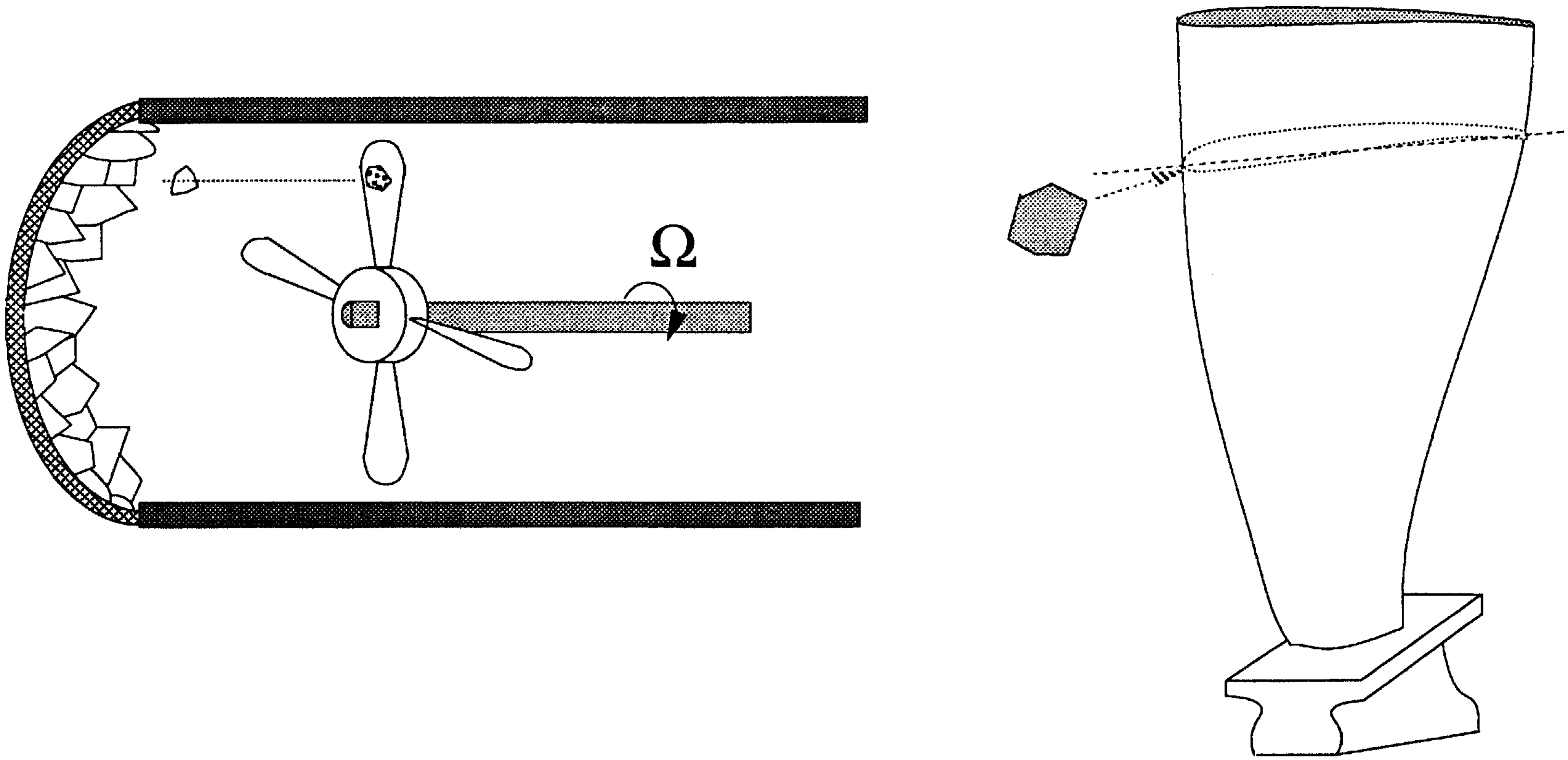


Figure 1. A Schematic of Ice Impact on an Engine Blade

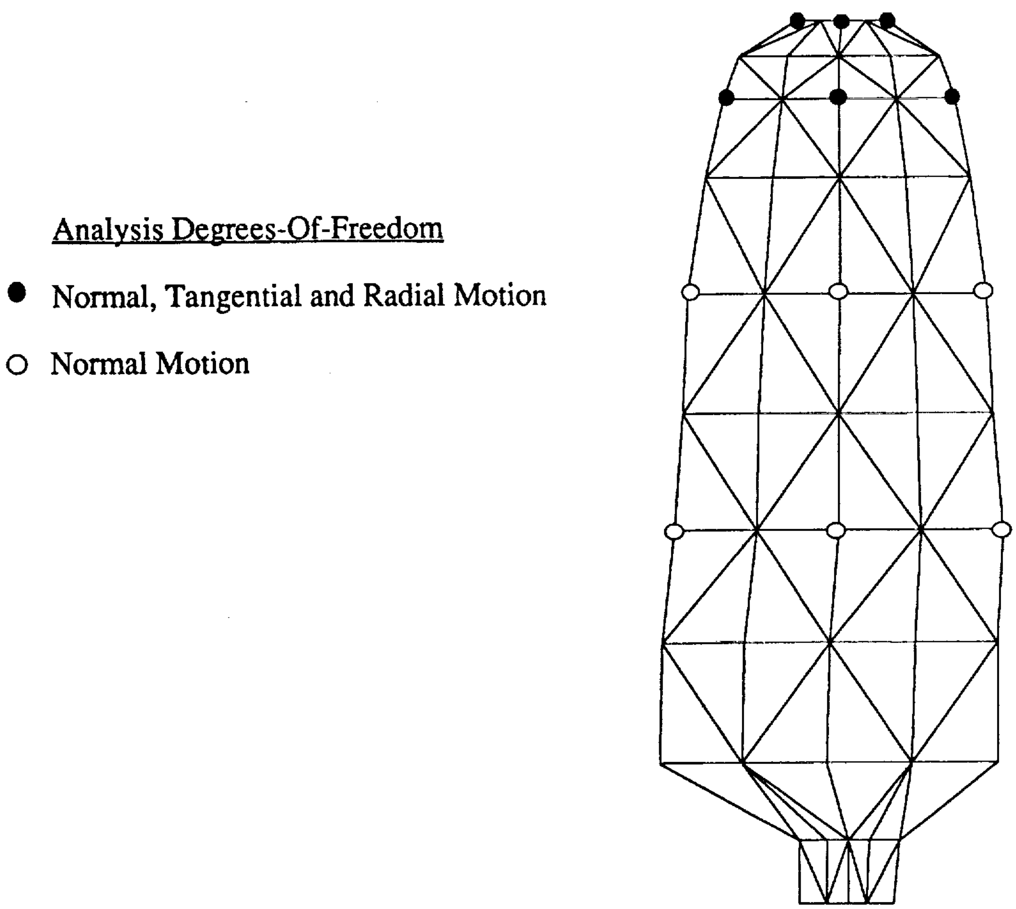


Figure 2. Blade Finite Element Model

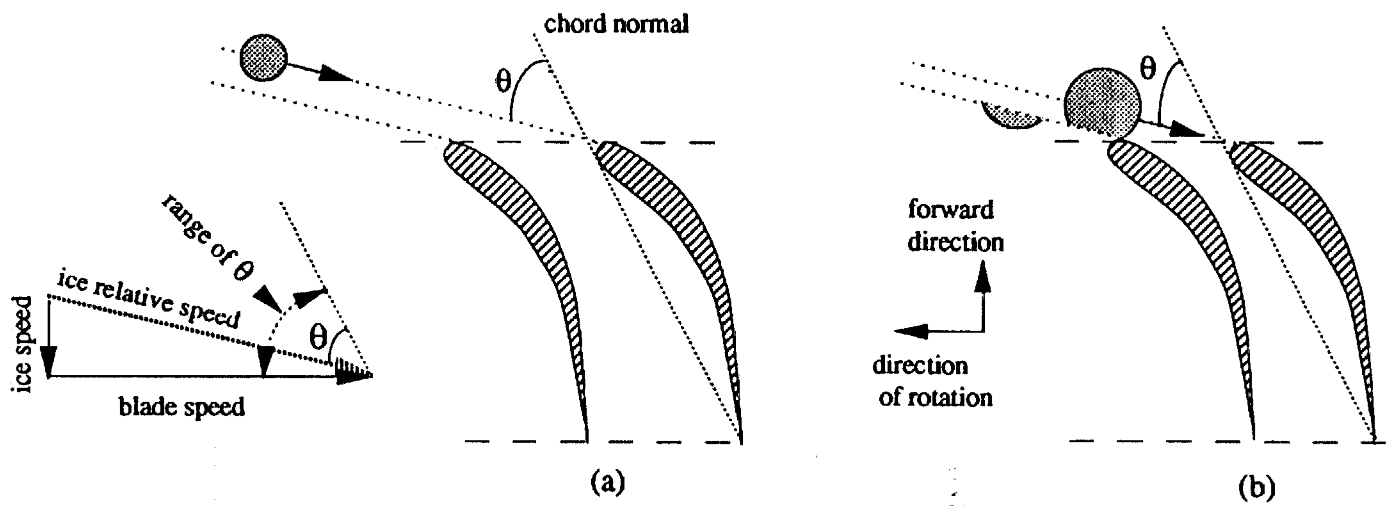


Figure 3. Geometry of Ice Impact on an Engine Blade

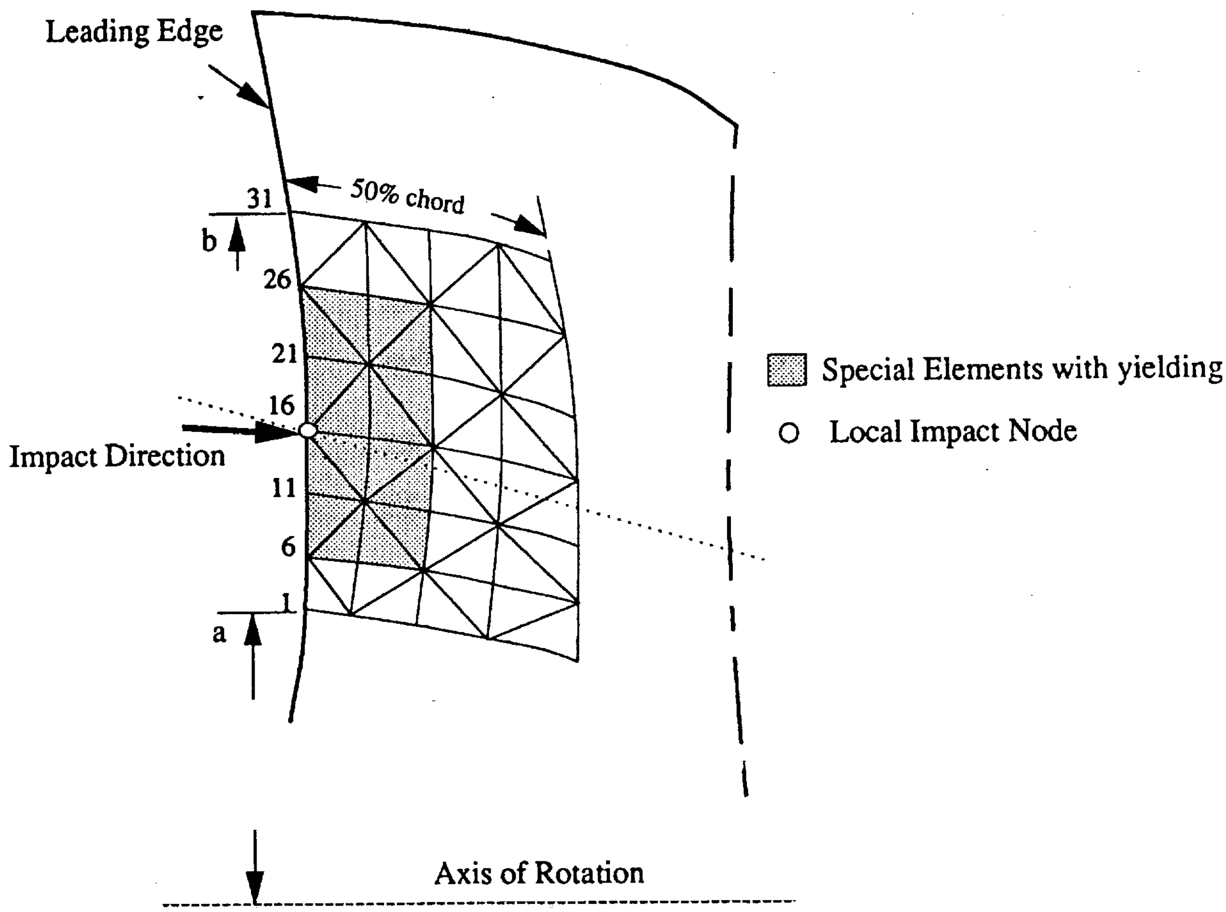


Figure 4. Finite Element Model for Local Ice Impact Analysis

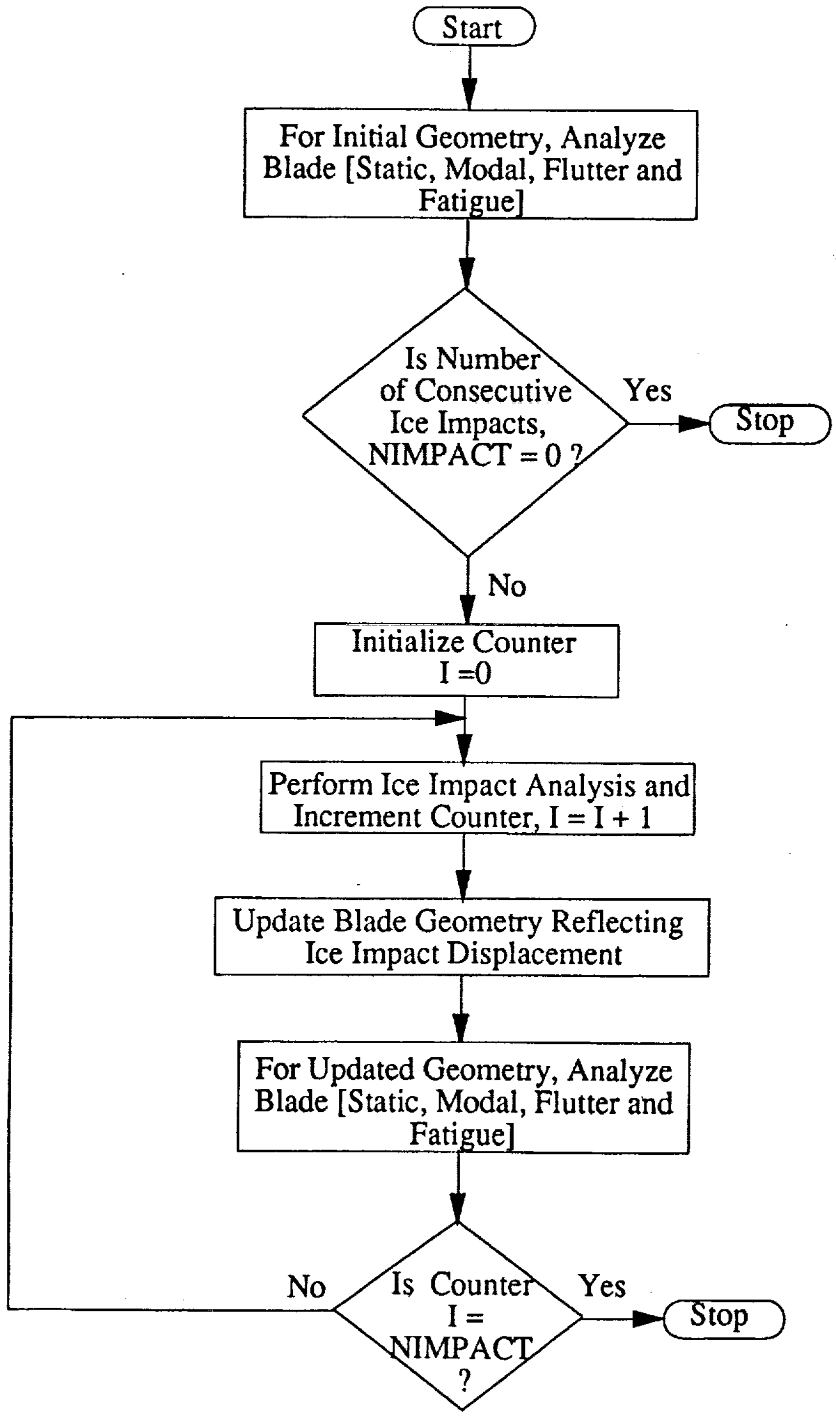
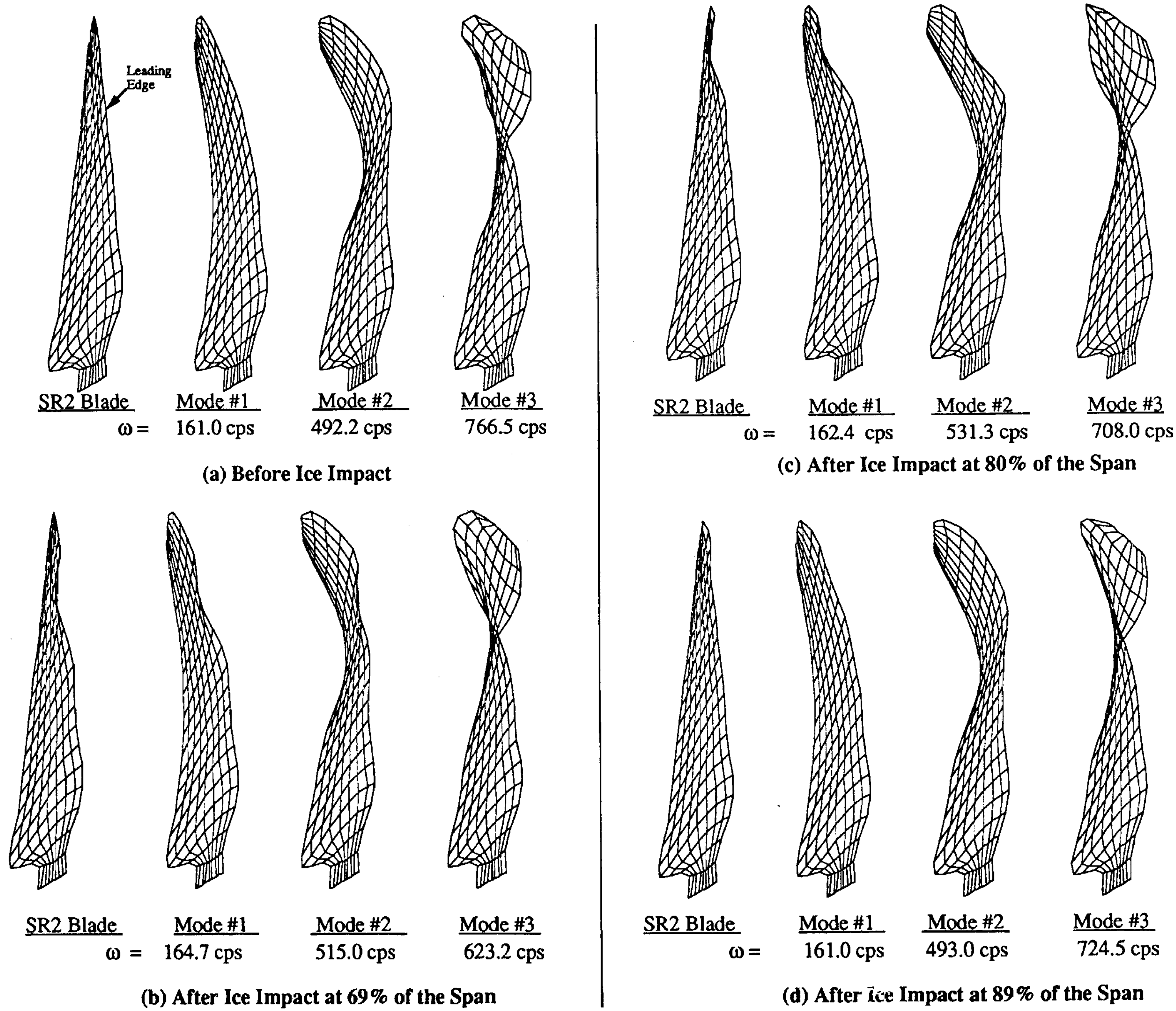


Figure 5. Geometry Update Process for Automatic and Consecutive Ice Impact Analysis



Engine Speed = 4000 RPM, Ice Velocity = 120 Knots, Ice Radius = 0.8 inch

Figure 6. Effect of Ice Impact Location on the Blade and its Mode Shapes

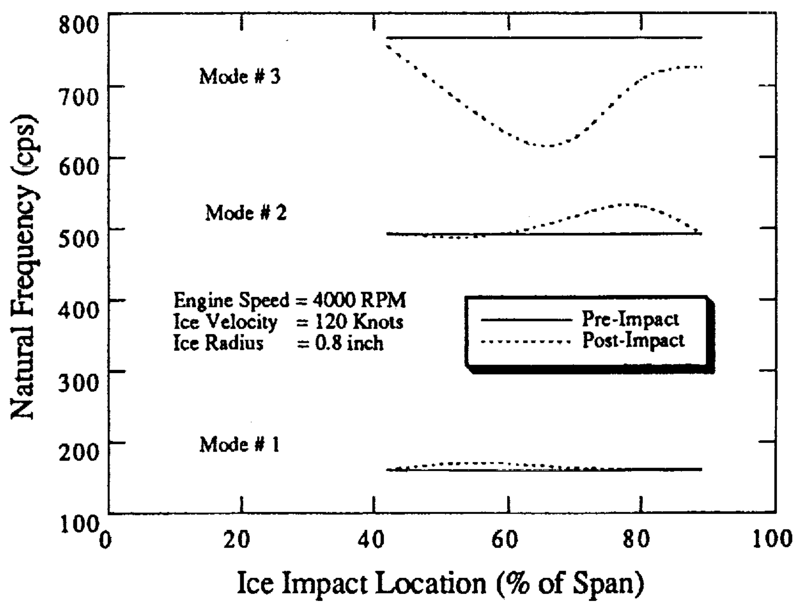


Figure 7. Variation of Natural Frequency with Ice Impact Location

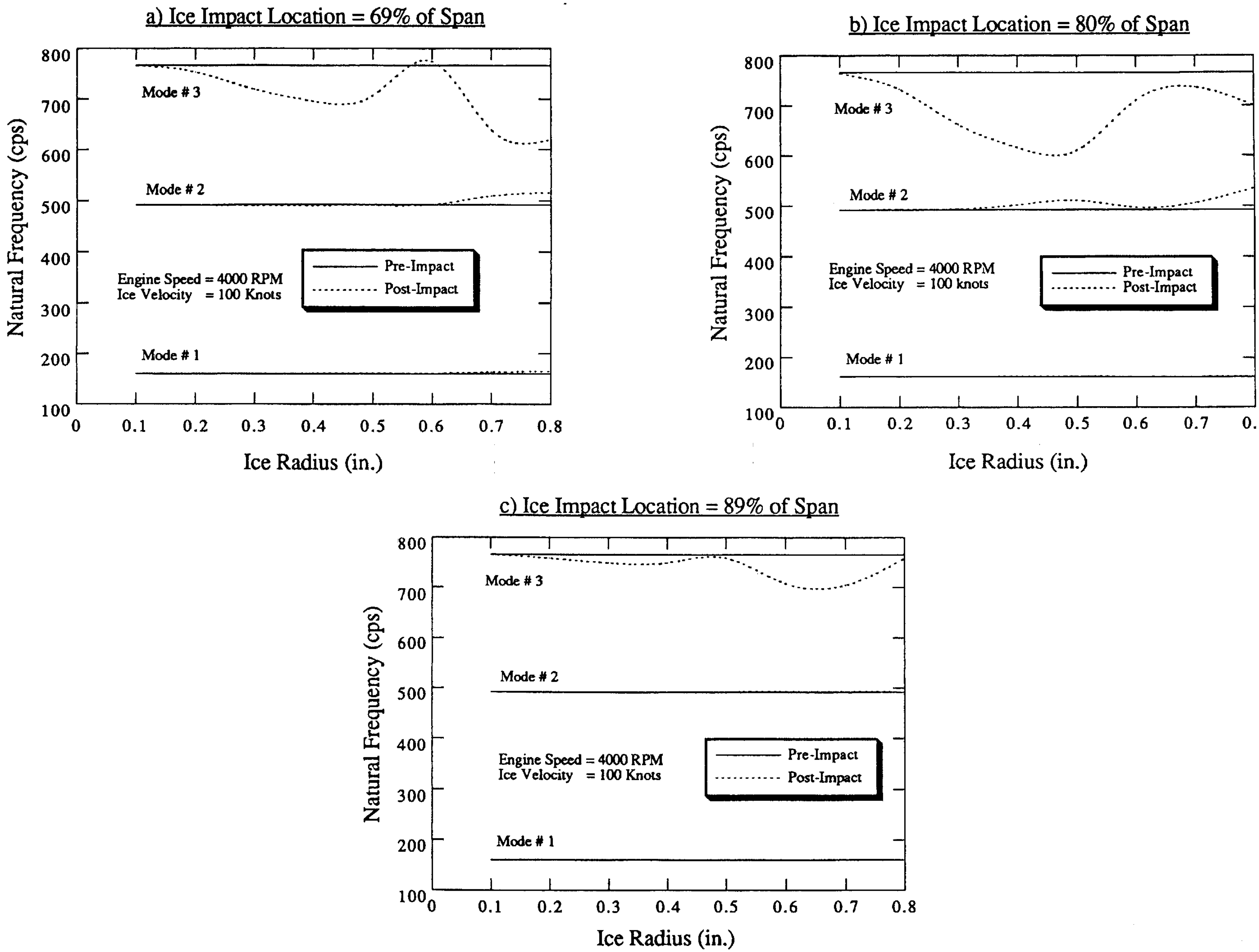


Figure 8. Variation of Natural Frequency with Ice Radius

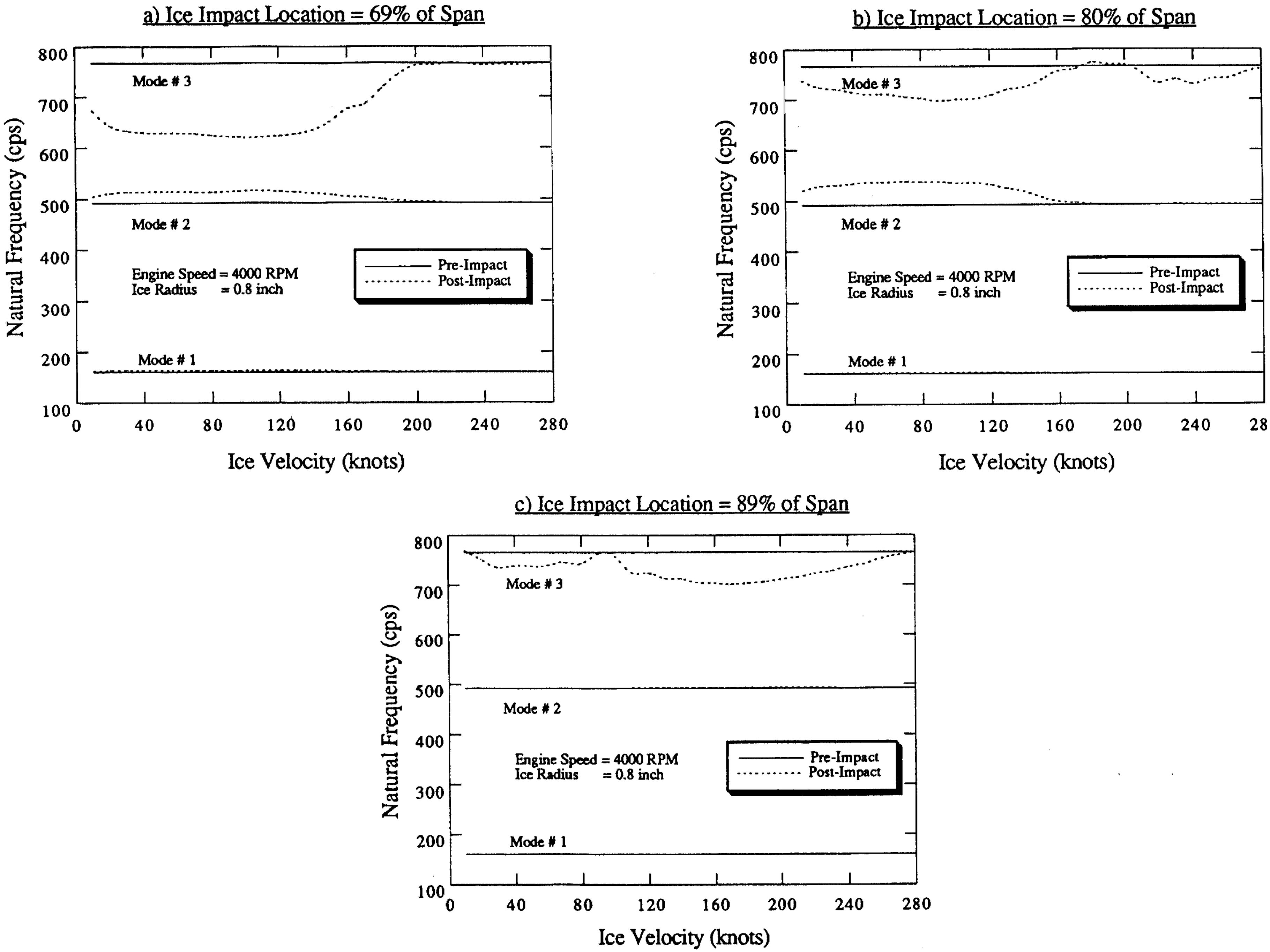


Figure 9. Variation of Natural Frequency with Ice Velocity

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13. ABSTRACT ***(Maximum 200 words)***

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