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AIRFRAME STRUCTURAL DYNAMIC CONSIDERATIONS IN ROTOR DESIGN OPTIMIZATION

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SUMMARY

The paper gives an overview and discussion of those aspects of airframe structural dynamics that have a strong influence on rotor design optimization. Primary emphasis is on vibration requirements. The vibration problem is described, the key vibratory forces are identified, the role of airframe response in rotor design is summarized, and the types of constraints which need to be imposed on rotor design due to airframe dynamics are discussed. The paper concludes with some considerations of ground and air resonance constraints on rotor design.

INTRODUCTION

The helicopter design process is a combination of all the major engineering disciplines aimed at meeting a wide variety of requirements (fig. 1). Clearly, the design process is multidisciplinary in nature. Although not indicated in figure 1, the design process is also interdisciplinary in character. Because of the complexity of the total design problem, the tendency has been to address the design problems in each of the contributing disciplinary areas as though they were independent (see, for example, figures 2 and 3). Thus, the design process has been traditionally treated as a sequence of essentially independent design activities. It is clear that such a sequential approach does not, in general, lead to a design which is optimum with respect to all the disciplines. A truly effective design process requires an integrated multidisciplinary approach which fosters the necessary synergism. Structural optimization techniques, if properly brought to bear by the design engineer, could play a key role in establishing such an integrated approach to helicopter design.

The NASA Langley Research Center and the Army Aerostructures Directorate have recently undertaken a major research program which is aimed at developing an integrated, multidisciplinary, optimization-based approach for rotorcraft design (ref. 1). Initial attention under this program is being directed to design optimization of rotors only, with the airframe design assumed to be prescribed and therefore not subject to design changes. As a further expedient, the airframe is also assumed to be decoupled from the rotor and the influence of airframe dynamics is to be accounted for in terms of design requirements (constraints) on the rotor blades. The purpose of this paper is to provide an overview and discussion, both in rather broad terms, of those aspects of airframe structural dynamics that have a strong influence on rotor design optimization. Primary emphasis is on vibration requirements. The vibration problem is described, the key vibratory forces are identified, the role of airframe response in rotor design is summarized, and the types of constraints which need to be imposed on a rotor design due to airframe dynamics are discussed. The paper concludes with some considerations of ground and air resonance constraints on rotor design.

VIBRATIONS

The Problem

Helicopters are susceptible to vibrations due to the inherent cyclic nature of the airloads acting on the rotor blades. The vibrations normally pervade both the rotor and the airframe (fig. 4) and can seriously degrade both service life and ride qualities. Vibrations also frequently limit the maximum speed in forward flight. While considerable progress has been made over the past forty years in reducing the level of vibrations in helicopters, the reduction has, for the most part, been achieved through the use of add-on vibration control devices. These devices, while quite effective in reducing vibrations, have usually had significant weight penalties associated with them.

Even though excessive vibrations have plagued virtually all new helicopter development programs, until recently, helicopter manufacturers have relied little on analysis during design in their efforts to limit vibrations. With only a few exceptions, helicopters have been designed to performance requirements while relying on past experience to account for vibrations. Excessive vibrations were then "tinkered out" during ground and flight testing. However, because of the vibration problems encountered during two recent major helicopter development programs, there has emerged a consensus within the industry on the need to account for vibrations more rigorously during both the analytical and experimental phases of design. This need has resulted in the subject of helicopter vibrations receiving considerably increased attention in recent years (ref. 2). The goal (unofficially) set down by the industry is to achieve the vibration levels associated with fixed-wing aircraft, the so-called "jet smooth" ride (ref. 3). To achieve this goal will require the development of advanced design analysis methodologies and attendant computational procedures which properly and adequately take into account vibrations requirements. These procedures will also have to account for the interdisciplinary nature of the design process.

Vibration design can be broadly classified into three interdependent activities: (1) Use of traditional design techniques to select rotor and airframe parameters which yield low inherent vibrations; (2) Design of vibration control devices to (further) reduce rotor and airframe vibrations; and (3) Vibration testing to verify design concepts and to compensate for any deficiencies in analytical capabilities. The interactive nature of these activities is depicted in figure 5. The diagram indicates that the helicopter vibration design cycle involves analytical and experimental considerations of the rotor, the airframe, and the coupling between the rotor and the airframe. This paper is concerned with only the first of the three activities noted above, that is, the use of traditional rotor and airframe design techniques to limit inherent vibrations.

Various types of analyses are used to support rotor and airframe design work. Special- and general-purpose rotor aeroelastic analysis codes are used to evaluate designs for acceptable rotor/hub vibratory loads. Finite-element models of varying complexity are used to verify adequate placement of airframe natural frequencies with respect to rotor excitation frequencies. Comprehensive rotorcraft aeroelastic analyses suitable for use in vibrations design work and which account for the coupling between the rotor and the airframe are under development. These efforts include both improving existing analyses and developing new analyses. Those analyses which have become available have not yet reached the level of maturity required for use in practical design work.

Key Vibratory Forces

The most significant vibrations arising in a helicopter are caused by the cyclic airloads acting on the blades of the main rotor. These loads are transmitted to the hub and down the shaft into the airframe as vibratory forces and moments. There are also other generally less important sources of vibration such as the tail rotor and the impingement of the main rotor wake on the tailboom and empennage. For steady-state flight conditions, the vibratory loads acting both on the rotor and on the airframe are periodic (fig. 4). The harmonic content of these periodic loads is indicated in figure 6. The periodic airloads acting on the rotor blades contain frequencies Ω, 2Ω, 3Ω, . . . , $n\Omega$, where Ω is the rotor rotational speed in radians per second. The loads which are transmitted from the rotor to the airframe are also periodic. However, if the blades are perfectly matched (as assumed here), the shears and moments acting at the roots of the individual blades sum in such a way that the resultant forces and moments which act on the airframe occur only at frequencies which are integer multiples of $N\Omega$ (the so-called blade passage frequency), where N is the number of blades. Thus, the airframe is excited by forces which are at frequencies $N\Omega$, $2N\Omega$, $3N\Omega$, . . . , $nN\Omega$. The oscillatory forces which act on the airframe at the frequencies $nN\Omega$ are generated by blade oscillatory forces which occur at frequencies $nN\Omega$ and $(nN \pm 1)\ \Omega$ when viewed in a coordinate system which is rotating with the blade. Because the magnitude of the harmonic airloads generally decreases with increasing harmonic number, the lower harmonics of the blade airloads are usually more important with respect to vibrations than the higher harmonics. For the airframe then, the largest vibratory forces acting on the airframe are usually those occurring at the frequency $N\Omega$.

Role of Airframe Response

The major source of vibrations in helicopters, as already mentioned, arises from the cyclic airloads acting on the blades of the main rotor. The dynamic characteristics of the rotor and the airframe and the coupling of these two systems determine the manner in which the helicopter responds dynamically to these oscillatory loads. It has long been recognized that the dynamic (and aerodynamic) interaction between the rotor and the airframe is important in analysis of helicopter vibrations. However, the complexity of the problem is so overwhelming that it has been customary to compute the blade (and hence rotor) vibratory loads assuming that the rotor is operating in a trimmed flight condition but with its hub fixed. The loads are then applied to separate analytical models of the rotor and the airframe for determining their respective vibratory responses. It is clear that this approach cannot account for the dynamic interactions between the rotor and the airframe. A simplified view of how the rotor and the airframe interact to produce vibrations is depicted in figure 7. Due to the periodic nature of the airloads acting on the blades of a rotor, the blades respond dynamically and the resulting vibratory loads are transmitted to the airframe causing it to respond. The resulting airframe motions cause the hub to vibrate which alters the aerodynamic loading on the blades and hence the loads transmitted to the airframe. Depending on the type and configuration of the hub, this interaction can substantially affect the vibrations in both the rotor and the airframe.

Because of increasing demands for further reductions in vibrations to achieve the goal of a "jet smooth" ride, it is now recognized that the simplistic approach described above for accounting for vibrations during design is no longer adequate. Analysis methods which accurately account for the coupling between the rotor and the airframe must be employed in design analyses. Practical computational implementations of the analysis methods are also needed. As previously mentioned, comprehensive rotorcraft aeroelastic analyses suitable for vibrations design work and which account for the coupling between the rotor and the airframe are under development. The problem of defining computational procedures for the coupled system which are suitable for use during structural design is also being addressed. For example, reference 4 establishes foundations for the adequate representation and treatment of the airframe structure in design analysis of helicopter vibrations.

Among the practical methods for calculating the vibrations of a rotor and an airframe as a single system, those methods that are based on impedance matching techniques which effect a solution in the frequency domain rather than in the time domain appear to be better suited for use in design work. The impedance coupling technique has been widely used for the vibration analysis of mechanical systems which are composed of an assembly of point-connected components. While the method has been known to the helicopter community for many years and has been employed in analysis of helicopter vibrations (see, for example, refs. 5-7), it has not been used extensively in design to limit vibrations. In the application of the method to the solution of the coupled rotor-airframe problem, a trimmed flight condition must first be established for the aircraft. The loads acting on the airframe at the hub are then given by the sum of the rotor hub vibratory loads (both forces and moments) calculated by assuming that the hub is fixed at the attitude angles determined by the trim solution and a (linear) correction term which accounts for small oscillatory hub motions away from trim. The gross vibratory forces exerted by the rotor on the airframe are given by the fixed-hub forces. The fixed-hub forces come from the solution of the underlying nonlinear aeroelastic equations for the rotor with the hub fixed at the attitude angles determined from a trim solution. The correction term is the so-called rotor hub impedance matrix and represents a correction to the gross rotor forces resulting from small motions of the rotor from equilibrium. The rotor impedance matrix is obtained by imposing small oscillatory motions on each of the rotor hub degrees of freedom at the airframe excitation frequencies which are of interest (i.e., $N\Omega$) and calculating the resulting hub loads required to maintain that motion. Changes in the vibratory hub loads per unit hub motion in each rotor hub degree of freedom are then computed. These loads constitute the columns of the impedance matrix. (For zero forcing frequency the impedance matrix reduces to the familiar stiffness matrix). The rotor hub impedance matrix is square, generally complex, and of a size equal to the total number of degrees of freedom associated with the interface point(s) between the rotor system and the airframe system. For a single point interface, such as at the point where the hub is connected to the shaft, the maximum number of degrees of freedom is six. The impedance matrix of the airframe at its interface with the rotor is calculated in a similar manner. Compatibility relations are then written for the interface forces and displacements leading to a set of coupled equations in terms of impedances. The resulting "harmonic balance" equations are a set of simultaneous linear algebraic equations which are solved for the hub motions, from which the airframe (and rotor) vibrations are computed.

Constraints Imposed on Rotor Design

As mentioned earlier, in this paper the airframe structure is assumed to be prescribed and not subject to design changes. Now the design of a rotor which, when coupled to an existing airframe, will result in low vibration levels in the airframe requires knowledge of the latter's dynamic characteristics. Because the airframe design is fixed, it is assumed that its dynamic description in terms of both its frequency response characteristics and its frequencies, mode shapes, and modal structural damping are known. It is also assumed that the airframe hub impedance can be computed for the excitation frequencies of interest (which depend on the number of blades and the rotor rotational speed). The purpose of this section is to identify the types of constraints which airframe dynamics imposes on rotor design from the perspective of vibrations requirements.

The requirement for low vibratory response of the airframe to excitation from the rotor necessitates: (1) Insuring that none of the frequencies of the major airframe modes is close to the predominant rotor exciting frequencies; and (2) Minimizing the rotor induced loads which are transmitted to the airframe.

The proximity of airframe modal frequencies to rotor exciting frequencies as well as the level of airframe vibratory response under excitation are usually determined by inspection of frequency response functions which are computed (or measured) for the airframe structure. Frequency response curves typically have the form depicted in figure 8, which shows the airframe response (usually the acceleration in g's) at some point (and direction) as a function of hub excitation frequency. Usually, many curves of this kind are generated corresponding to each unique combination of the location of the excitation point (the hub is assumed in these discussions) on the airframe, the type (force or moment) and direction (vertical, lateral, etc) of excitation, and the response points and directions of interest. The "peaks" on the curve occur at the natural frequencies of the airframe; the higher peaks correspond to modes which are major contributors to the total response. The "valleys" represent low levels of response.

As previously mentioned, the oscillatory loads acting on the airframe occur at integer multiples of NΩ. Because the magnitude of these loads typically decreases with increasing harmonic number, usually only NΩ (and sometimes 2NΩ) need be considered in practice, as suggested by figure 8. Now the number of blades and the rotor rotational speed are generally determined by aerodynamic requirements early in design. Usual practice is to then design the airframe to avoid any frequencies which would result in either resonance or high amplification at NΩ (and perhaps 2NΩ). However, because the airframe design is assumed to be fixed, the design requirement here is to select N and Ω such that the rotor excitation frequencies NΩ and 2NΩ are sufficiently removed from the frequencies of the major airframe modes.

The airframe natural frequencies are strongly dependent on the dynamic characteristics of the rotor and thus its effect needs to be included in the calculated (or measured) frequency response functions for the airframe. To satisfy this requirement, the mechanical impedance of the rotor is usually taken into account approximately by including an "equivalent" rotor mass in the airframe finite-element model. If the airframe design is assumed to be fixed, it may be inappropriate to require recalculation of the airframe frequency response functions at each iteration in the rotor design optimization process to account for the changing rotor weight. However, because the weight of the initial rotor design will usually not be too much different from the weight of the final design, an equivalent rotor mass based on the initial weight can be used in the calculation of the frequency responses for the (fixed) airframe design.

Once adequate separation of the rotor exciting frequencies from the major airframe natural frequencies has been established, the remaining step to achieving low vibratory response in the airframe is the reduction of the magnitude (with due attention to phase) of the rotor oscillatory forces and moments which are transmitted to the airframe. This, in effect, requires the reduction of the resultant vibratory shears and moments acting at the roots of the individual blades. There are several design approaches which may be employed to effect this reduction. Some of these are discussed below.

Traditional rotor blade design practice for the reduction of blade vibratory response under airload excitation is based on the criterion of blade frequency placement. The objective in this approach is to maintain adequate separation between the rotating natural frequencies of the blade modes and the frequencies of the periodic airloads acting on the rotor blades over the operating range of rotor rotational speeds. This assessment is usually done with the aid of a blade frequency diagram, such as the one shown in figure 9 for an articulated rotor. The figure shows the variation of the blade frequencies with rotor rotational speed. The radial lines emanating from the origin represent aerodynamic excitation frequencies which occur at harmonics of the rotor speed. Whenever a natural frequency of the blade coincides with one of the lines representing a harmonic of rotor speed, the blade is in a state of resonance. Whether the blade responds excessively at resonance depends on whether there is sufficient aerodynamic excitation at that frequency to drive the mode in question and on the amount of structural and aerodynamic damping which is present. As already pointed out, the rotor loads transmitted to the airframe occur at frequencies $nN\Omega$ (see fig. 8). These loads are a result of the blade vibratory responses which, when viewed in a rotating coordinate system, have frequencies $nN\Omega$ and $(nN\pm1)\,\Omega$. This suggests that for a low vibration airframe the design requirement for blade frequency placement is to maintain adequate separation of the blade frequencies from $nN\Omega$ and $(nN\pm1)\,\Omega$. This will require placing upper and lower bound constraints on the frequencies of the blade modes. However, because the magnitude of the harmonic airloads generally decreases with increasing harmonic number, attention to only the lower harmonics corresponding to $n = 1,2$ would probably suffice in design work.

A blade design which is optimized for blade frequency placement does not guarantee a low vibration airframe. If this approach does not prove adequate, resort must be made to other approaches. Most alternative methods which appear to be well suited for design optimization work are based on directly reducing the resultant shears and moments which act at the roots of the individual blades, rather than indirectly by the method of frequency placement. Such alternative methods could be employed either subsequent to, or in lieu of, a blade design based on the frequency placement criterion, depending on the particular formulation. If such methods are employed as an adjunct to the use of a frequency-based approach, the design established based on frequency placement would provide the initial design for the direct minimization of the blade root shears and moments. The required blade root shears and moments can be calculated using blade aeroelastic analyses formulated to compute such quantities. However, because the aeroelastic equations which underlie these analyses are normally highly nonlinear, such an approach may not be well suited to optimization work where repetitive analyses are required. Approaches based on the use of estimates for the blade root shears and moments which are computed by means of simpler (approximate) expressions probably need to be employed if such methods are to gain acceptance in rotor design optimization work. Two such expressions which appear to be well suited to serve in this capacity have been described in the literature (see, for example, refs. 8-10). The expressions, one for "modal shears" and the other for "modal vibration indices", are contributors to the complete expression for the blade root shear obtained from a solution of the equation of motion for the generalized response of the ith blade mode to harmonic airload excitation. The modal shear expression is the simpler of the two and only requires knowledge of the blade mass distribution and its natural modes and frequencies. The vibration indices are directly dependent on the modal shears, but also require knowledge of the blade generalized mass, the aerodynamic forcing function, and the dynamic amplification factor for the blade. Whichever type of expression is used, it would need to be evaluated only for the blade modes which are major contributors to the blade vibratory response. Also, in the calculation of the generalized aerodynamic force which appears in the expression for the vibration indices, an approximate aerodynamic loading would be assumed to simplify the computations.

Depending on the formulation of the optimization problem, it may be useful to impose constraints on the resultant forces and moments which are transmitted to the airframe rather than on the shears and moments which act at the roots of the individual blades. As previously mentioned, for a coupled rotor-airframe system in a trimmed flight condition, the loads acting on the airframe at the hub are given by the sum of the rotor hub loads calculated assuming that the hub is fixed and a correction term dependent on the rotor hub impedance matrix. If one were dealing with the coupled system, it would be appropriate to impose constraints on the resultant forces. However, for the rotor design problem in which the rotor is assumed to be decoupled from the airframe, use of the fixed-hub forces alone is appropriate. Because the fixed-hub forces give the gross vibratory loads acting on the airframe, these should give a good approximation to the total transmitted load.

The computations for blade frequencies which lead to frequency diagrams such as that shown in figure 9 are usually based on the assumption of a fixed hub; that is, the impedance (resistance) presented to the rotor by the airframe at the hub is taken to be infinite. In practice the impedance is finite and it is well known that in this situation the blade natural frequencies and mode shapes can be substantially different from what they are for a fixed hub. In this case, the effects of hub flexibility should probably be included in any calculation of the blade modes and frequencies. This can be done by determining the relevant airframe hub impedance matrix (or some approximation to it) and including it in an appropriately formulated blade dynamic analysis (see, for example, refs.11 and 12). The inclusion of hub flexibility in the blade dynamic analysis should lead to improved estimates of frequencies for use in a blade frequency placement approach. The corresponding blade modes should also be improved and could be used in rotor aeroelastic analyses to calculate improved estimates of the blade root shears and moments and fixed-hub rotor forces which are employed in constraint equations.

Several types of vibration problems involving the coupling of the rotor/engine/drive train combination with the airframe have been encountered in helicopter development programs (see, for example, ref. 13 and references cited therein). This experience has shown that some blade frequencies may be substantially affected by the dynamics of the drive train system. This suggests that the impedance characteristics of the drive train at the rotor hub may also have to be included in the determination of the blade modes and frequencies. If the drive system is considered part of the airframe (which design is assumed fixed), then it may impose an additional constraint on the permissible range of values of rotor speed for a new rotor design. This is because the dynamic characteristics of the drive system (e.g., shaft critical speeds) are usually matched to the rotor/engine/airframe system during design.

GROUND AND AIR RESONANCE

Aeromechanical instabilities are phenomena in which the inertial coupling between the motion of the first inplane blade mode and any airframe mode that involves hub motion in the plane of the rotor produces a growing oscillation. This may occur on the ground (ground resonance) or in flight (air resonance). Because the airframe dynamics play an important role in these instabilities, it seems appropriate to briefly address rotor design requirements as they might be affected by consideration of these instabilities.

Early studies of ground resonance (ref. 14) showed that this type of instability can occur only when the rotating natural frequency of the blade's first inplane mode, ω_L, is less than the rotor rotational speed, Ω, and when the difference between the rotor speed and this blade frequency, $\Omega-\omega_L$, coincides with, or is close to, a frequency of one of the airframe modes having inplane hub motion. Thus, ground resonance is only a problem on articulated and soft-inplane hingeless rotors, both of which have $\omega_L < \Omega$. The instability is purely mechanical, deriving its energy from the shaft torque, and does not develop from aerodynamic forces. (However, aerodynamic forces may affect the level of damping.) The critical airframe modes in ground resonance are typically those associated with essentially rolling and pitching motions on the landing gear.

Air resonance is a similar type of instability which can occur when a helicopter is in flight (see, for example, ref. 15). Both stiff-inplane ($\omega_L > \Omega$) and soft-inplane ($\omega_L < \Omega$) rotors can be susceptible. The instability, if it occurs, is associated with a frequency coalescence of the absolute value of the quantity $\Omega-\omega_L$ with the frequency of an airframe mode containing inplane hub motion. However, unlike ground resonance where the dominant stiffness arises from the landing gear structure, the frequency of the critical airframe mode in the case of air resonance is determined primarily by the aerodynamic stiffness associated with the blade flapping motion. Air resonance is generally not a problem in articulated and stiff-inplane hingeless rotors but must be considered for soft-inplane hingeless rotors.

Assessment of both ground and air resonance can be made from plots of the type shown in figure 10, which illustrates how the pertinent airframe and rotor mode frequencies (all expressed with respect to a fixed coordinate system) vary with rotational speed for both hingeless and articulated rotors. For simplicity, the uncoupled rotor and airframe frequencies are shown in figure 10. The open circles denote points of frequency coalescence between the critical rotor modes and an airframe frequency and are regions of potential instability. The amount of structural or viscoelastic damping present determines whether the system responds excessively at resonance and goes unstable. The rotor design requirement is to insure that, within the operating speed range of the rotor, there are no coincidences of the frequency of the critical rotor mode with an airframe mode and that sufficient damping is present.

CONCLUDING REMARKS

An overview and discussion has been presented of those aspects of airframe structural dynamics that have a strong influence on rotor design optimization. Primary emphasis was placed on vibration requirements. The vibration problem was described, the key vibratory forces were identified, the role of airframe response in rotor design was summarized, and the types of constraints which need to be imposed on rotor design due to airframe dynamics were discussed. Some considerations of the influence of ground and air resonance on rotor design were also discussed.

REFERENCES

1. Adelman,H.M.; and Mantay, W.R.: Integrated Multidisciplinary Optimization of Rotorcraft: A Plan for Development. NASA TM 101617 (AVSCOM TM 89-B-004), May 1989.

2. Kvaternik, R.G.; Bartlett, F.D.,Jr.; and Cline, J.H.: A Summary of Recent NASA/Army Contributions to Rotorcraft Vibrations and Structural Dynamics Technology. Proceedings of the1987 NASA/Army Rotorcraft Technology Conference, NASA CP 2495, pp. 71-179.

3. Gabel, R.: The Future: When Helicopter Smooth Surpasses Jet Smooth. Keynote Address. AHS National Specialists' Meeting on Helicopter Vibration, Hartford, CT, Nov. 2-4, 1981.

4. Kvaternik, R.G.; and Walton, W.C., Jr.: A Formulation of Rotor-Airframe Coupling for Design Analysis of Vibrations of Helicopter Airframes. NASA RP-1089, June 1982.

5. Gerstenberger, W.; and Wood, E.R.: Analysis of Helicopter Aeroelastic Characteristics in High-Speed Flight. AIAA J., vol. 1, no. 10, Oct. 1963, pp. 2366-2381.

6. Novak, M.E.: Rotating Elements in the Direct Stiffness Method of Dynamic Analysis With Extensions to Computer Graphics. Shock and Vibration Bulletin, Bull. 40, Pt. 4, Oct. 1969, pp. 41-46.

7. Staley, J.A.; and Sciarra, J.J.: Coupled Rotor/Airframe Vibration Prediction Methods. Rotorcraft Dynamics, NASA SP-352, 1974, pp. 81-90.

8. Blackwell, R.H.: Blade Design for Reduced Helicopter Vibrations. Journal of the American Helicopter Society, Vol. 28, No. 3, July 1983, pp. 33-41.

9. Davis, M.W.; and Weller, W.H.: Application of Design Optimization Techniques to Rotor Dynamics Problems. Presented at the 42nd Annual National Forum of the American Helicopter Society, Washington, DC, June 2-4, 1986.

10. Taylor, R.B.: Helicopter Rotor Blade Design for Minimum Vibration. NASA CR 3825, October 1984.

11. Weller, W.H.; and Minick, R.E.: An Improved Computational Procedure for Determining Helicopter Rotor Blade Natural Modes. NASA TM 78670, August 1978.

12. Wood, E.R.; and Buffalano,A.C.: Parametric Investigation of the Aerodynamic and Aeroelastic Characteristics of Articulated and Rigid (Hingeless) Helicopter Rotor Systems. U.S. ArmyTRECOM Technical Report 64-15, April 1964.

13. Twomey, W.J.: Review of Engine/Airframe/Drive Train Dynamic Interface Development Problems. Proceedings of the AHS Specialists' Meeting on Helicopter Propulsion Systems, Williamsburg, VA, November 6-8, 1979.

14. Coleman, R.P.; and Feingold, A.M.: Theory of Self-Excited Mechanical Oscillations of Helicopters With Hinged Blades. NACA Report 1351, 1958.

15. Donham, R.E.; Cardinale, S.V.; and Sachs, I.B.: Ground and Air Resonance Characteristics of a Soft-Inplane Rigid-Rotor System. Journal of the American Helicopter Society, Vol. 14, No. 4, October 1969, pp. 33-41.

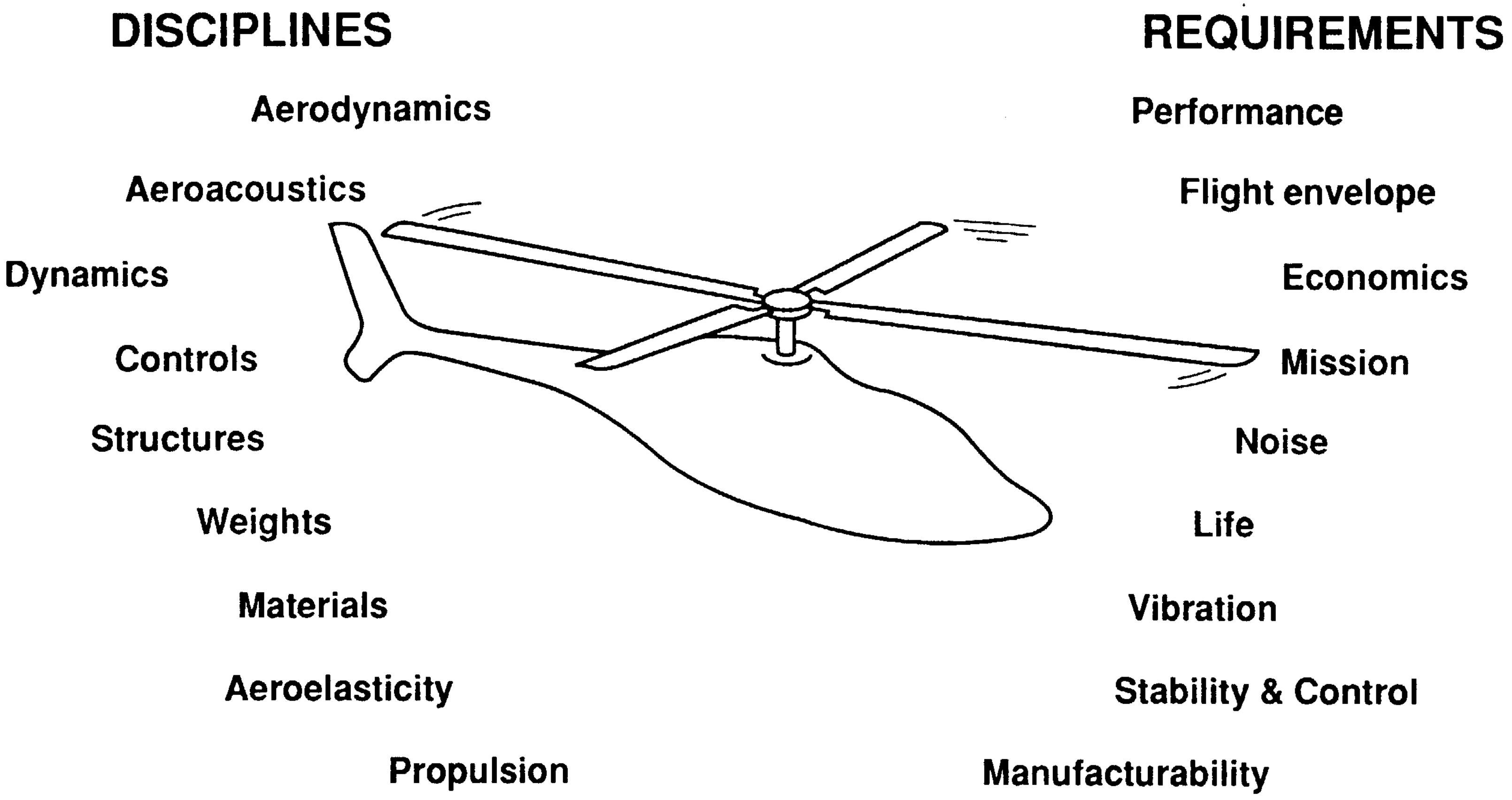


Figure 1.- The interdisciplinary nature of helicopter design.

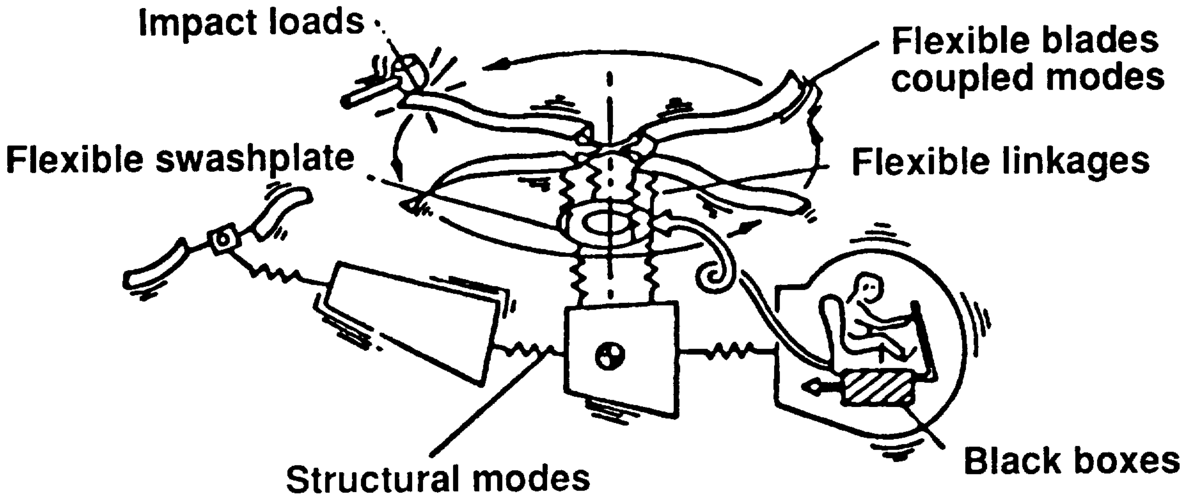


Figure 2.- The helicopter as might be viewed by a dynamicist.

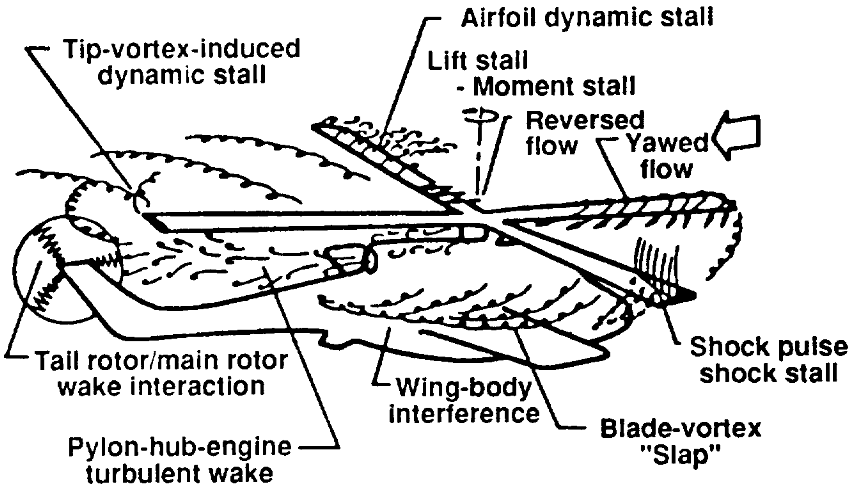


Figure 3.- The helicopter as might be viewed by an aerodynamicist.

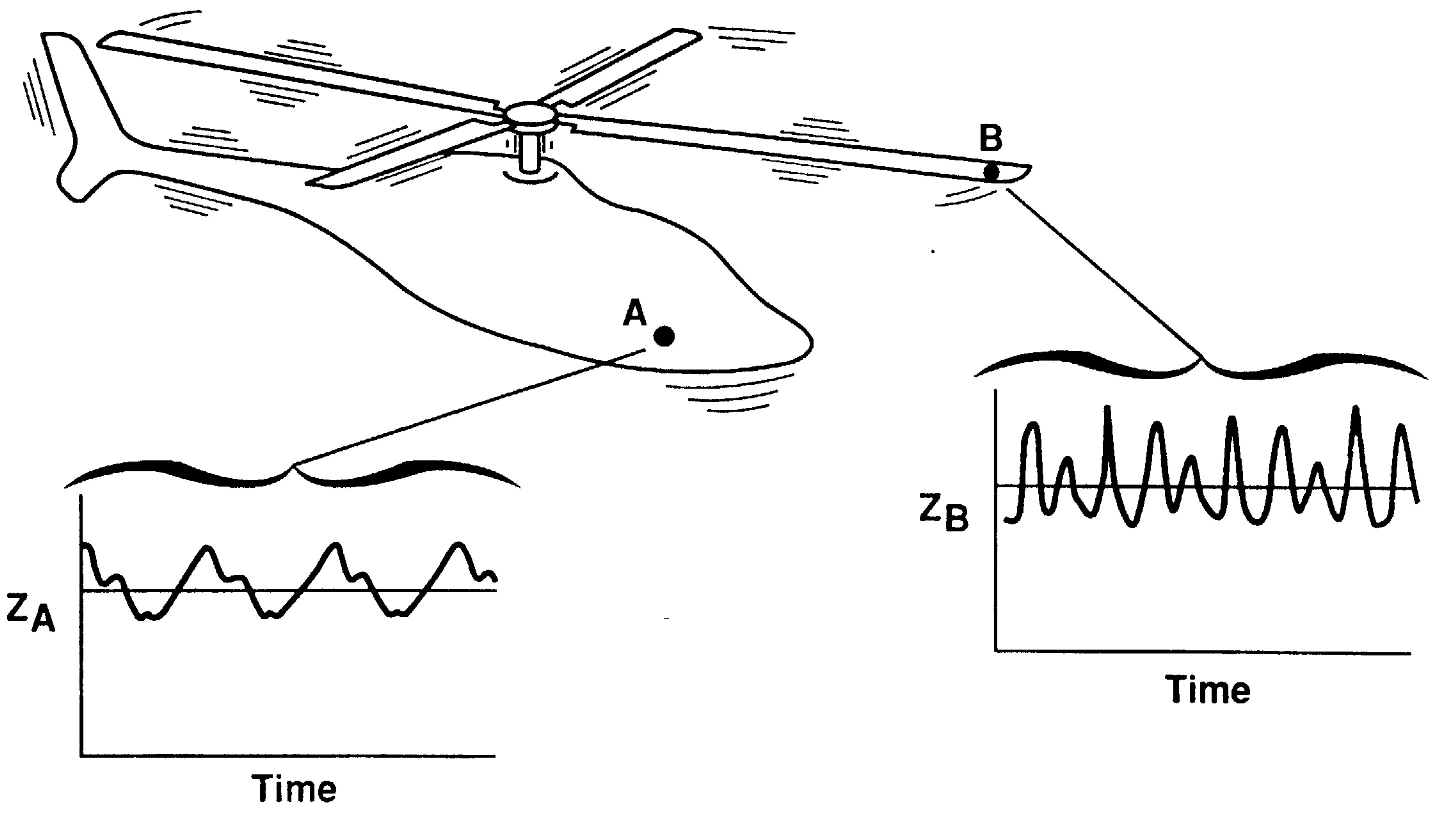


Figure 4.- Steady-state vibrations of a flexible helicopter in steady flight.

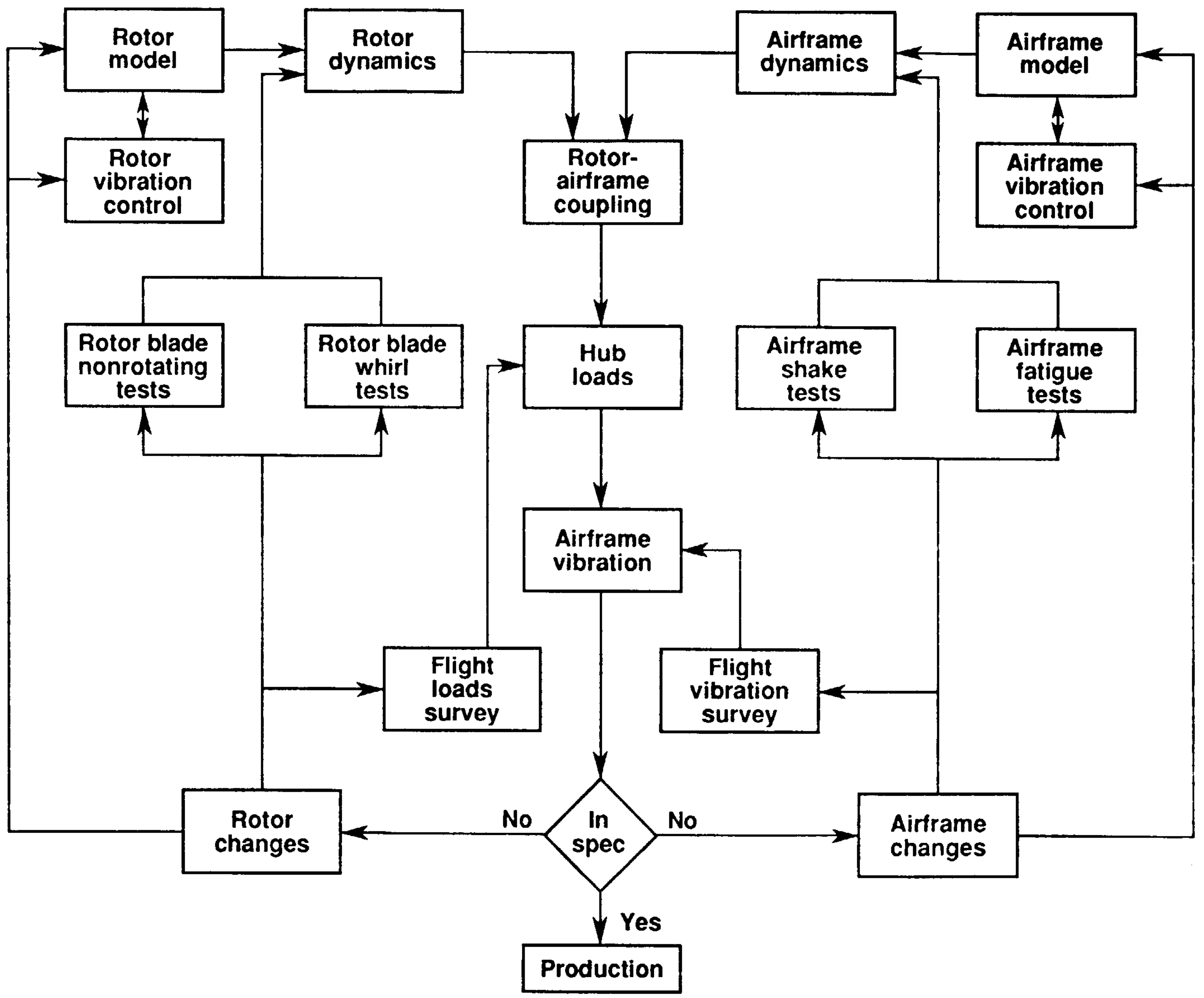
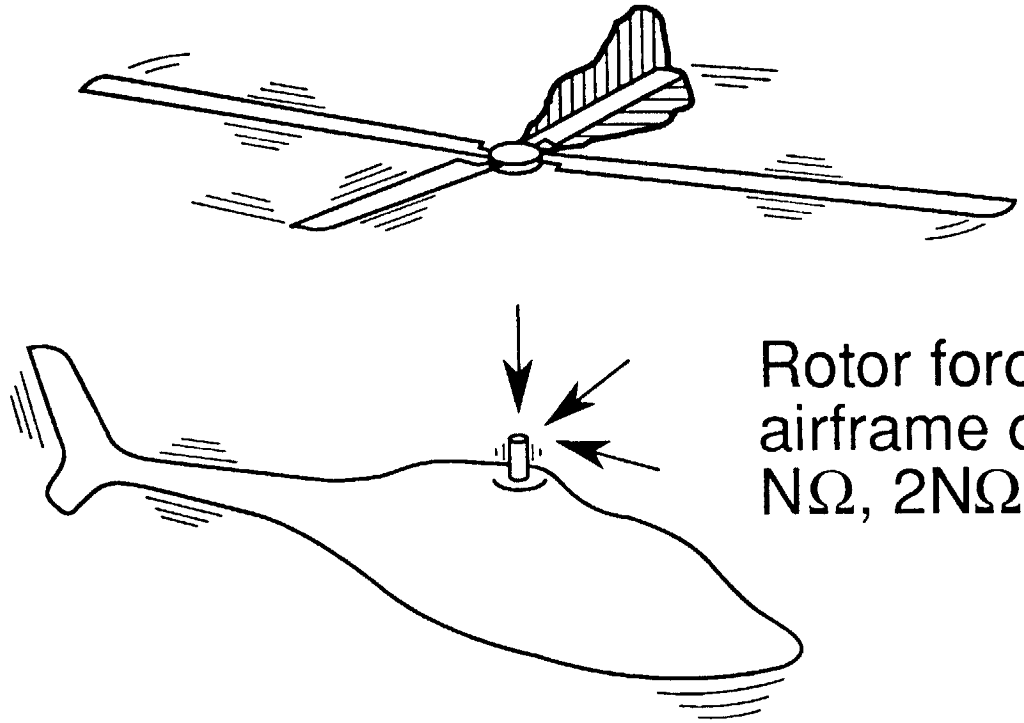


Figure 5.- One view of the helicopter vibration design cycle.

Periodic airloads acting on rotor blades contain frequencies Ω, 2Ω, 3Ω, 4Ω, ...



Rotor forces transmitted to airframe contain frequencies $N\Omega$, $2N\Omega$, $3N\Omega$, ...

Ω = Rotor rotational speed
N = Number of blades

Figure 6.- Oscillatory forces important in helicopter vibrations.

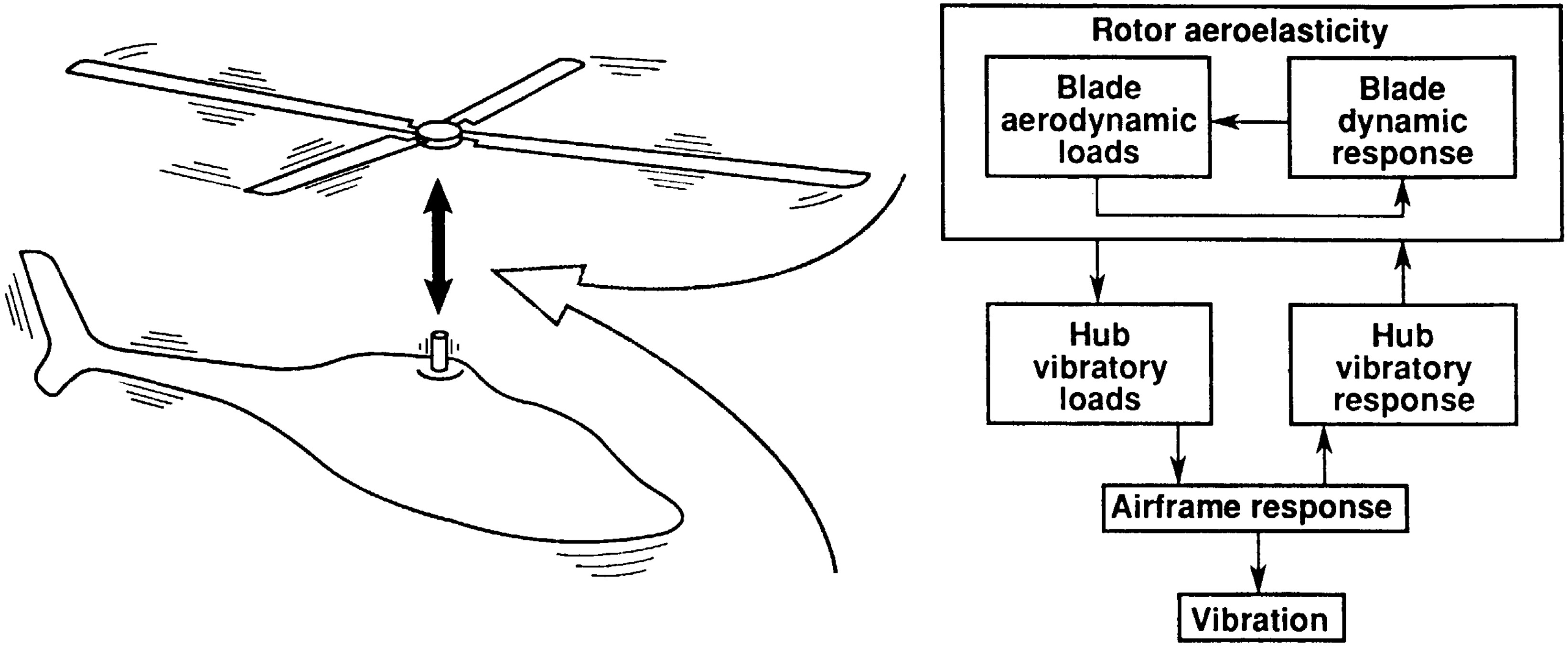


Figure 7.- A simplified view of rotor-airframe interaction in producing vibrations.

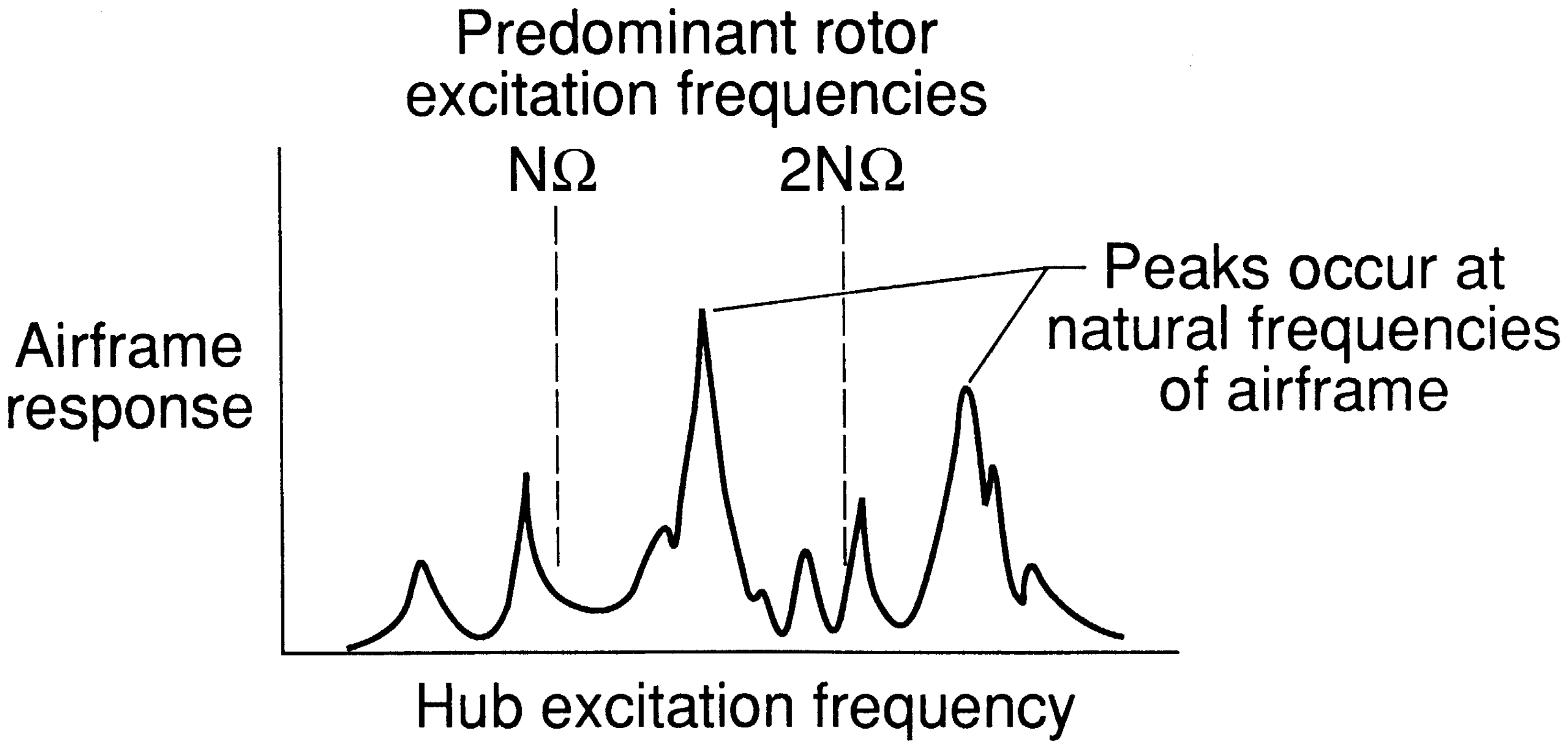


Figure 8.- Typical variation of airframe response with hub excitation frequency.

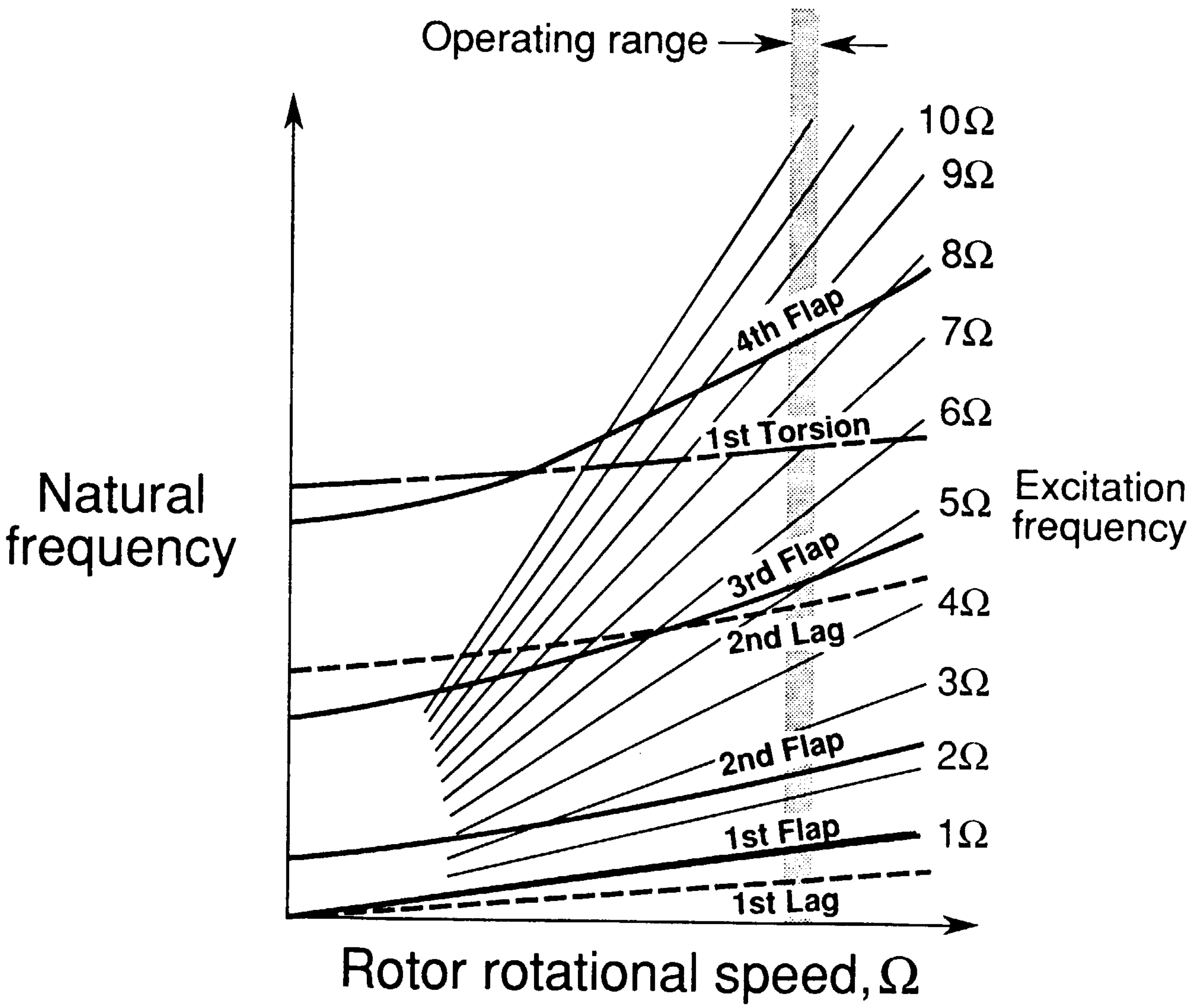
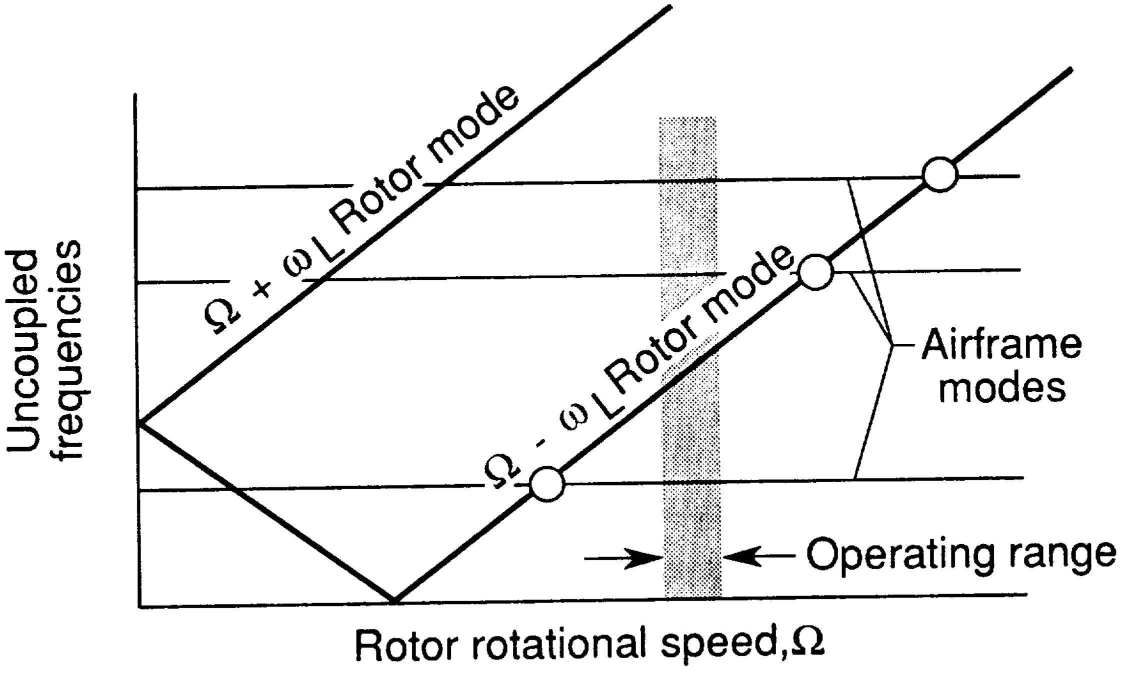
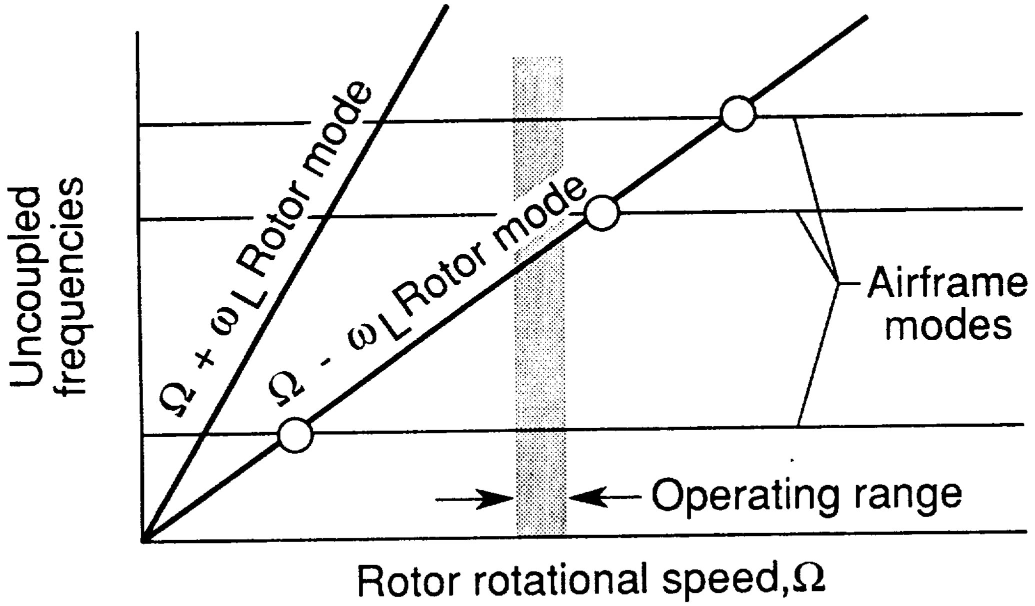


Figure 9.- Typical variation of blade natural frequencies with rotor speed for an articulated rotor.



(a) Hingeless rotor



(b) Articulated rotor

Figure 10.- Typical variation of uncoupled rotor and airframe frequencies with rotor rotational speed for assessment of ground and air resonance.

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16. Abstract

The paper provides an overview and discussion of those aspects of airframe structural dynamics that have a strong influence on rotor design optimization. Primary emphasis is on vibration requirements. The vibration problem is described, the key vibratory forces are identified, the role of airframe response in rotor design is summarized, and the types of constraints which need to be imposed on rotor design due to airframe dynamics are discussed. The paper concludes with some considerations of ground and air resonance as they might affect rotor design.

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