Experimental Study on Flutter in Cascading Blades

(1st Report, Measurement of the Aerodynamic Damping Force Acting on Cascading Blades Vibrating in Translatory Mode)

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For the purpose of investigating the aerodynamic damping effects on vibrating cascade blades, the authors made a water tunnel with a linear cascade in which five blades vibrate in a translatory mode with arbitrary frequency and phase angle between the adjacent blades.

A series of experiments were carried out on an isolated blade and on the cascades with the following conditions:

Blades: NACA 65-(12) 10 (fixed: 8, vibrating: 5) chord: 30 mm span: 60 mm solidity: 1 stagger angle: 0°, 30° amplitude of vibration: 2 mm

The experimental results were analyzed by comparing with the theoretical ones hitherto obtained and with the aid of the considerations about the quasi-steady force of vibrating blades.

Introduction

Blade failure due to vibration, which had been a troublesome problem in the inception of the turbojet engine, has recently come up again as a problem as the axial-flow compressors with higher compression ratio are in use.

The blade failures due to vibration may be attributed to the excitation phenomena which are divided into several categories as follows:

1. The periodic passage of the blades through the wakes of other obstacles.
2. The self-excited oscillation of flow which causes a blade vibration, bringing about the failure due to resonance or fatigue.
3. Rotating stall and surging belong to this category.
4. Self-excited vibration of the blade itself, which is called flutter and may arise in a uniform flow in both unstalled and stalled states.

Since the higher compression ratio makes the off-design performance of axial-flow compressor more critical, the front stages being liable to stall, rotating stall and stall flutter seem to play rather important roles in blade failures. In any case it would be impossible to remove completely these excitations because of the complexity of the phenomena, and the most dangerous of them can only be removed or averted at best by cut-and-try methods.

For the prediction of the possibility of blade vibration, it is essential to know the aerodynamic and mechanical damping effects on the vibrating cascade blades. Considering especially the importance of the role of the aerodynamic damping effect in blade vibration, and for the purpose of investigating this problem, the authors have made a water tunnel with a linear cascade which has a few blades vibrating in a translatory mode with arbitrary frequency and interblade phase difference.

A series of experiments on an isolated blade and cascading blades were carried out.

Experimental apparatus and procedure

Halfman et al., for an isolated blade, and Schnitger, for a cascade, realized the experimental apparatus which oscillates a single blade mechanically in arbitrary conditions and measured the aerodynamic forces acting on it.

In a cascade test, however, it is necessary to oscillate all or at least a few blades in a cascade with arbitrary phase difference between the adjacent ones, because the mutual interference between the blades cannot be ignored.

For lack of any experimental apparatus that satisfies such requirements as mentioned above, we made on trial a water tunnel equipped with a linear cascade. In this cascade, a few blades can be vibrated by our devised mechanism with arbitrary frequency and inter-blade phase difference under
several cascade conditions.

Detailed descriptions of the apparatus and procedures are in the following sections (see the specifications in Appendix).

**Vibration mode and fluid substance**

The experiments hitherto made on turbomachines or cascades show that the blade vibration takes nearly the form of a fundamental flexural mode and many of the troublesome failures of blades occur in this mode. On the other hand, a pitching vibration seems to be considered to have not so significant effect on the blade failures as a flexural one.

From such considerations, blade vibration in a translatory or flexural mode was treated in this experiment.

The translatory blade vibration brings about a change of the angle of attack, nearly equal to \( \dot{\alpha} = \omega \delta / U \), which induces an aerodynamic force of about \( \pi \rho U^2 \dot{c} \alpha \) per unit span of blade, where \( \omega \): angular velocity of blade vibration, \( \delta \): amplitude of vibration, \( U \): velocity of flow, \( c \): blade chord. The inertia force of the blade is \( m \omega^2 \dot{\alpha} \) (\( m \): blade mass per unit span).

Then

\[
\text{aerodynamic force due to vibration} = \frac{4}{\mu k} \\
\text{inertia force due to vibration} = \mu k
\]

where

\[
\mu = \frac{m}{\pi \rho(c/2)^2} : \text{mass ratio} \\
k = \frac{\omega c}{U} : \text{reduced frequency (usually smaller than 1)}
\]

In the method of force measurement mentioned later, mass ratio must be sufficiently small (e.g. \( \mu < 1 \)) in order to separate precisely the aerodynamic force from the inertia force. By comparing the several methods that make the mass ratio small, this problem was solved by the adoption of water as fluid substance, making the use of solid metal blades possible and the apparatus simple and small.

**Water tunnel**

For the purpose of supplying the test section with water we manufactured a water tunnel which is the same as the wind tunnel except the use of water (see Fig.1).

Water stored in an underground tank (1) is elevated by a pump (2) into a head tank (3), which can always provide water under a constant head with an overflow. Then the water, passing through a pressure tank (4) and a settling section (5), enters the test section (6). The water coming out of the test section flows over the wall of an exit pressurization tank (7), returning into the underground tank.

**Linear cascade of vibrating blades**

Test section is so designed that the aerodynamic force acting on blades vibrating with arbitrary frequency and inter-blade phase angle may be measured under any optional condition of cascade, with the aim of analyzing the aerodynamic damping on a vibrating cascade blade, the time delay of boundary layer separation and so forth.

It has a linear cascade between parallel circular discs in the same way as a usual 2-dimensional linear cascade test rig, as shown in Fig.2. There are installed thirteen blades, five of which in the central position of the cascade may be shaken by
mechanical oscillators.

The mechanism of oscillators, which vibrate some of the blades in translation with arbitrary frequency and optional inter-blade phase angle, is shown in Fig. 3 by perspective representation. A vibrating blade 1, fixed on the block of the scotch yoke 2 through a cantilever 3, is hung on the circular side plate 4 by leaf springs 5 parallel to the blade chord. The blade may therefore move only in the direction normal to the blade chord, corresponding to the bending motion in a usual annular cascade.

An electric variable-speed motor moves the blade through a gear train 6, crank wheel 7 and scotch yoke mechanism in this order.

The amplitude of blade vibration can be varied by the exchange of the setting position of the crank wheel, and the vibrating frequency by the speed change of motor. Then many kinds of vibrating cascade conditions may be obtained.

The aerodynamic force is measured on the center blade by the use of strain gages 8 attached on the root of the cantilever and the displacement of blade by the strain gages 9 patched on the springs.

The protection against water leakage from the holes through which the blade shafts protrude and against the submersion of strain gages is provided by gum mantles 10 and 11.

On the other hand, the other vibrating blades are supported and oscillated at both their ends. At first the center blade was also supported in the same manner. But the inevitable mismatching in the motions of both ends of the blade, bringing errors into the aerodynamic force measurement, made it necessary to hang the center blade by a cantilever.

**Experimental procedure and record analysis**

The Wheatstone bridge composed of four strain gages, two of which are attached on the root of the cantilever, is sensible only to the normal-to-chord component of the force acting on the blade.

Signals from strain gages are fed into Cathode Ray Oscillograph and ink-writing oscillograph through appropriate amplifiers and filters (see Fig. 4). On CRO, for example, the abscissa and ordinate corresponding to the displacement and force of the blade respectively, a closed loop may be observed in every cycle of the blade vibration (see Fig. 5). The area of this loop corresponds to the work done on the flow by the blade or the aerodynamic damping energy supplied for the blade.

![Fig. 3 Mechanism of blade vibration](image)

![Fig. 4 Measuring circuits](image)

![Fig. 5 Record on CRO](image)

* Crank wheel, the inter-blade phase angle of vibration by the change of.
For the analysis of aerodynamic force it would be necessary in general to subtract the inertia force of blade from the force measured by such a method mentioned above, because the latter consists of aerodynamic and inertial ones.

However, when this loop on CRO may be taken as ellipse, it is not necessary to subtract the inertia force from the total one so far as only the aerodynamic damping effect is considered, because at that time the aerodynamic damping force is proportionate to the half width of the loop at the zero displacement of the blade.

The author's experiments showed that the loop on CRO had a form resembling closely the ellipse not only in uninstalled state but also in the vicinity of the stall point. This is due to the reason that the translatory vibration of blade brings relatively a smaller change in the angle of attack and aerodynamic force.

Then in this report, treating the phenomenon in the regions of the cascade condition where the loop may be taken as ellipse, the experimental data were analyzed only from the view point of aerodynamic damping force, as mentioned above, without subtraction of the inertia force of blade. But, because of a slight, inevitable fluctuation of the loop, the analyses of the experimental data were carried out on a few cycles of the phenomenon recorded on the ink-writing oscillograph in the same way as on the loop.

The coefficients of the aerodynamic forces are defined as follows.

Static force
\[ C_F = F/H_1S \]  \hspace{1cm} (1) \hspace{1cm}

Aerodynamic damping force
\[ -\tilde{C}_D = -f_D/H_1S \left( \frac{\eta}{c} \right) \] \hspace{1cm} (2) \hspace{1cm}

where
- \( F \): static aerodynamic force normal to blade chord
- \( f_D \): aerodynamic damping force
- \( H_1 \): dynamic pressure of flow far upstream of blades
- \( S \): area of blade

The calibration of the strain gages which measure the normal-to-chord component of the aerodynamic force is done by hanging weights at several points on the chord-line of the midspan of blade. This test showed that practically the output of the strain gages had nothing to do with the chordwise location of the weight or aerodynamic center and also was not interfered by the force of chordwise direction.

The displacement of blade is measured by the strain gages on the leaf springs and the frequency of the blade oscillation is counted by a magnetic method.

The velocity of an incoming flow is measured by a Prandtl tube upstream of the cascade.

The testing procedures are as follows:
1) Taking out water from the tunnel and testing section, the measuring instruments are adjusted.
2) Oscillating the blade with appropriate frequency in the empty tunnel, the records of the inertia force of blade are taken.

Simultaneously inspections are made about whether the blades are free from the other circumferential disturbances or not.
3) Supply water in the tunnel.
4) Setting the blade at a given inlet angle, check up the balance of the measuring instruments.
5) Then the wind-on tests (pouring water) are conducted; firstly to obtain the static characteristics of the cascade and secondly to obtain the aerodynamic characteristics of the vibrating blade in several kinds of cascade conditions.

**Experimental results**

**Experimental conditions**

The experiments reported herein were conducted under the following conditions of cascade. (see Fig.6)

Blade profile: NACA 65-(12) 10, Chord length \( c \): 30 mm, Aspect ratio: 2, Solidity \( c/s \): 1, Angle of stagger: \( \theta = 0^\circ \) and \( 30^\circ \) (for compressor), Interblade phase difference: \( \varphi = 0^\circ, \pm 60^\circ, \pm 120^\circ, 180^\circ \) (positive when the blade vibrates in advance of the concave-sided blade).

Reduced frequency: \( \tilde{f} \equiv \omega e/W_1 = 0.04, 0.08, 0.12, 0.18, 0.24, 0.34 \) (treating the region of a relatively small \( \tilde{f} \) where usually the stability of the blade vibration comes into question).

Amplitude of vibration: \( \delta = 2 \) mm, Velocity of incoming flow: \( W_1 = 3.14 \) m/sec

**Experimental results for an isolated blade**

Here will be shown the experimental results for an isolated blade (using the compressor blade mentioned above).
Fig. 7 gives the characteristics of the normal (to chord) static force versus the angle of attack by a dotted curve. It can be seen that a stall occurs at $\alpha \approx 20^\circ$ over which the slope becomes once negative and restores again to a slightly positive slope for $\alpha > 30^\circ$.

Fig. 7 illustrates also the characteristics of the aerodynamic damping force $(-\xi_{fr})$ of the vibrating blade in a transitory mode, which are positive for all reduced frequency ($\frac{\Omega}{c}$) and for an overall region of the angle of attack.

In spite of the use of a compressor blade, the aerodynamic damping force at the zero angle of attack agreed well with the theoretical results for an isolated wing(3).

This figure shows that, as the angle of attack increases from zero, the aerodynamic damping force $(-\xi_{fr})$ decreases and takes the minimum value at $\alpha = 15^\circ \sim 20^\circ$, making an abrupt increase immediately thereafter. Within the region of the negative slope of normal force characteristics ($\alpha = 20^\circ \sim 30^\circ$), the periodic boundary layer separation irrelevant to the blade oscillation made it difficult to analyze the experimental results.

The theory for an isolated wing in uninstalled state(3) shows that the contribution of the wake to the aerodynamic damping force is smaller than twenty percent of that of the quasi-steady force for such reduced frequency as used here. Then it is expected that the characteristics of aerodynamic damping may be connected to the static normal-force characteristics by quasi-steady analysis.

Quasi-steady aerodynamic damping force for an oscillating blade in a transitory mode is obtained from Eq. (1) as follows:

$$\left(-\xi_{fr}\right)_{qs.} = \frac{dF}{H_{15}S \left( \frac{\partial}{\partial \alpha} \right)}$$

$$= k \left( 2C_F \sin \alpha + \frac{\partial C_F}{\partial \alpha} \cos \alpha \right) \cdots (3)$$

By such reasoning, the decrease of $(-\xi_{fr})$ in uninstalled state would be caused by the decrease of the slope of $C_F$-curve or $\partial C_F/\partial \alpha$. But this reasoning cannot be extended to explain the abrupt increase of the aerodynamic damping force in the vicinity of the stall point ($\alpha = 20^\circ$). This fact seems to be attributed mainly to the time delay of the boundary layer separation which may bring a different phase relation between the aerodynamic force and the motion from that in uninstalled state.

**Experimental results for cascading blades**

In this section the experimental results will be described firstly for the case of zero angle of stagger and secondly for the case of stagger angle of 30°. $\theta = 0$: The static characteristics of the normal force acting on the cascading blades, as shown in Fig. 8, show a monotonic increase of the normal force in the uninstalled state and also in the stalled state after its slope becomes once about zero.

At first the experimental results will be compared with the theoretical results for a vibrating cascade blade with finite spacing.

Among the theoretical studies, Sisto's theory(4) is the typical one for an oscillating cascade with finite spacing, giving the aerodynamic force acting on the vibrating cascade without a turning of flow. The authors' experimental results and Sisto's ones at the same condition of a cascade without a stagger and a turning of flow are compared in Fig. 9. It may be considered that there is a good agreement between the theory and the experiments, except at the in-phase vibration of all blades ($\varphi = 0$) when the effect of finite cascade would seem to appear most significantly.

![Fig. 7 Aerodynamic characteristics of an isolated blade](image1)

![Fig. 8 Normal force ($\theta = 0^\circ$)](image2)
From such a comparison, it would be reasonable to consider that this apparatus operates like an infinite cascade, in spite of its finite number of cascading and vibrating blades.

When all of the blades with a finite angle of attack vibrate in the same phase, the quasi-steady approach may be also applied as in the last section, because of the absence of a relative displacement between the blades that brings about a mutual interference of the adjacent blades. The static characteristics of normal force (Fig. 8) may be connected definitely to the characteristics of the aerodynamic damping [Fig. 10(1)] by the equation of quasi-steady force similar to Eq. (3) but using \( \alpha_1 - \theta \) instead of \( \alpha \).

An abrupt increase of \( -\tilde{C}_{fr} \) above \( \alpha_1 - 25^\circ \) seems to come not only from the positive slope of the static force but also from the time delay of the boundary layer in the stalled state.

When the blades vibrate with the phase difference from the neighbouring blades, a simple analysis as above-mentioned cannot be made because of the influence of the other blades.

Fig. 10(2) illustrates the result on the case of an anti-phase vibration or \( \varphi = 180^\circ \). In this figure there cannot be seen a so significant, steep increase of \( -\tilde{C}_{fr} \) in the stalled state as in the in-phase vibration.

Fig. 10(3), (4) give the results of the blade vibration with a phase angle of \( \pm 60^\circ \). They show that, in unstalled state, as the angle of attack increases, \( -\tilde{C}_{fr} \) has a tendency to increase at \( \varphi = +60^\circ \) and to decrease at \( \varphi = -60^\circ \) respectively. With further increase of the angle of attack \( -\tilde{C}_{fr} \) firstly decreases and restores above \( \alpha = 25^\circ \) (nearly stall point), in both cases. The recovery of \( -\tilde{C}_{fr} \) is significant especially at \( \varphi = +60^\circ \).

In Fig. 10(5), (6), the results for \( \varphi = \pm 120^\circ \) illustrate that their curves have intermediate features between those of \( \varphi = \pm 60^\circ \) and of 180°.

Fig. 10 shows also the disagreement of \( -\tilde{C}_{fr} \) at \( \alpha = 0^\circ \) for equal and opposite signed phase difference, which should not occur on blades with symmetric profile. The cause of this disagreement is not yet precisely determined.

Fig. 11 illustrates the dependence of the aerodynamic damping force on the inter-blade phase

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**Fig. 9** Aerodynamic damping (comparison with a theory)

**Fig. 10** Aerodynamic damping (\( \theta = 0^\circ \))
angle of vibration; for larger reduced frequency and smaller angle of attack, the aerodynamic damping tends to take its minimum value in the neighbourhood of $\varphi=0^\circ$ and, for smaller reduced frequency and larger angle of attack, this point travels to a larger positive phase angle.

$\theta=30^\circ$: Fig. 12 illustrates the static characteristics of a normal force acting on the blades cascading with a stagger angle of $30^\circ$.

When the blades vibrate in the same phase, the modified Eq. (3) for the aerodynamic damping force on the cascade is obtained from the quasi-steady approach and it may explain the relation between the characteristics of the static normal force and the aerodynamic damping force (Fig. 13(1)). The abrupt increase of $(-C_{fr})$ in the vicinity of the stall point as observed on the cascade without a stagger, however, cannot be experienced.

Fig. 13(3), (4), for the case of a phase angle $\varphi=\pm 60^\circ$, show that with an increase of the angle of attack, occurred a monotonic decrease of $(-C_{fr})$, the rate of which is larger in $\varphi=+60^\circ$ than in $-60$. For $\varphi=+60^\circ$ there may be seen a significant decrease of $(-C_{fr})$ near the region of the stall point, and then the aerodynamic damping becomes negative for all reduced frequencies applied here.

![Graphs and diagrams showing normal force and aerodynamic damping](Image)
Fig. 14 Inter-blade phase angle/Aerodynamic damping (θ = 30°)

Fig.14 illustrates the relation between the aerodynamic damping force and the inter-blade phase angle. This shows, more definitively than the case of zero stagger, that the larger the reduced frequency and the smaller the angle of attack becomes, the larger the phase difference becomes, at which the aerodynamic damping force is minimum.

Conclusion

The aerodynamic damping force on the cascade blades plays an important role in the rupture of blades in turbomachines.

For the purposes of measuring the aerodynamic damping force acting on the vibrating cascade blades precisely, the authors designed and manufactured a test rig of linear cascade of vibrating blades in a translatory (normal-to-chord) mode which operates in a water tunnel.

The experiments were done under the following conditions.

Blade: profile NACA 65-(12) 10, Chord: 30 mm, Span: 60 mm
Solidity: 1, Angle of stagger: 0° and 30° (for compressor)
Inter-blade phase angle and frequency of vibration: optional

The experimental results obtained by the use of this test rig are summarized as follows:

1) The aerodynamic forces acting on the vibrating blade in the region of a small angle of attack (unstalled state) have good approximation to those given by the theories in both isolated blade and cascade blades.

2) The small reduced frequency taken in this experiment makes it possible to apply the quasi-steady approach, which may connect the static characteristics and the aerodynamic damping forces.

3) In the stalled state, the time delay of boundary layer separation to the blade vibration seems to play a very important role, bringing about an increase of the aerodynamic damping, especially in an isolated blade.

4) When the blades vibrate in advance of the concave-sided blade, the decrease of the aerodynamic damping force with the increase of the angle of attack is generally larger than at the reversed condition of phase.

5) For larger reduced frequency and smaller angle of attack the aerodynamic damping becomes minimum nearly at the in-phase vibration. On the other side, for smaller reduced frequency and larger angle of attack the minimum damping may be obtained by a larger positive phase difference.

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Appendix

Specifications

Water circuit
1) Pump: Komatsu-Sulzer Helimax SP 25-30
Lifting head: 10 m, Flow rate: 15 m³/min
2) Pit: 2 m x 3.25 m x 2.5 m
3) Head tank: 2 m x 2 m x 1.2 m
Head: 7.5 m
4) Surge tank: inlet. 1.5 m x 2.5 m
outlet. 1.2 m x 1.2 m x 1.8 m
5) Nozzle: 60 mm x 300 mm (exit)
Contraction ratio: 17.7

Linear cascade of oscillating blades
1) Maximum flow velocity: 10 m/sec (Re = 3 x 10⁶)
2) Cascade: Blade: profile NACA 65-(12) 10, number 13 (5 vibrating blades), chord 30 mm, span 60 mm
3) Cascade conditions: pitch 30 mm (Solidity=1), inlet flow angle -15° ~ 75°, stagger angle -15°, 0°, 15°, 30°, 45°

3) Oscillating condition: frequency 0 ~ 50 cps, inter-blade phase angle 0° ~ ±180°, amplitude 0, 2, 3, 4 mm

References