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# An indirect torsional vibration receptance measurement method for shaft structures

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ABSTRACT

In this paper, an indirect method for measuring torsional vibration of shaft structures is established. In conventional torsional vibration measurement, knowledge of two fundamental quantities is needed: a torque applied to the system and the angle of twist thus produced, which are both difficult to measure in experiment. In this indirect method, neither a deliberate torque excitation system nor an angular transducer is needed. Instead, a T-like beam structure is introduced and attached to one end of a shaft structure whereby the torques are produced by ordinary forces and only linear accelerometers at a few locations of the beam structure are used. Through the small finite element model of the T-like beam structure, the torsional receptance linking the torque to the angle of twist of the shafting systems is derived from the measured receptances of linear acceleration to the excitation force. This indirect theoretical-experimental combined method overcomes the difficulties and the associated poor accuracy in measuring receptances of torsional vibration of shaft structures, and hence is very useful. Numerical simulation of a test structure with noisy parameters and noisy simulated receptance data is made to validate the theoretical soundness of the method. Vibration tests are carried out on a laboratory shaft structure to demonstrate its accuracy and ease of use.



## 1. Introduction

Shafts are common mechanical components that transmit mechanical power and withstand torques. In most cases, the torque a shaft bears would have a fluctuating component. When the frequency of this fluctuation is close to any torsional natural frequencies of the shaft, even a small torque can excite torsional resonance of the shaft and considerable damage may be caused to a machine such as fatigue failure, rapid bearing wear, gear hammering, fan belt slippage and often excessive noise problems [1–3]. Although many researchers have tried to measure frequency response function (FRF) data for rotational degrees-of-freedom (DOFs), only limited success has been made [4] and the accuracy of FRF of torsional vibration data is well known to be poor.

The problem of measuring torsional vibration can be tackled from two aspects: angular acceleration response measurement and torque excitation. Several techniques have been developed for torsional vibration tests based on measuring

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**Nomenclature**

| | |
|---|---|
| $\mathbf{B}_{ij}$ | Dynamic stiffness of the shafting system |
| $\tilde{\mathbf{B}}_{ij}$ | Dynamic stiffness of the T-like beam structure |
| $\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2$ | Vectors of displacements at connection point coordinates, other coordinates of the shafting system and other coordinates of the T-like beam structure, respectively |
| $\mathbf{f}_0, \mathbf{f}_2$ | Forces externally applied at connection point coordinates and other coordinates of the T-like beam structure, respectively |
| $w$ | Deflection in the $z$ direction (see Fig. 2) |
| $\theta_y$ | Rotational displacement about the $y$ axis |
| $\theta_z$ | Rotational displacement about the $z$ axis |
| $f$ | Translational force applied in the $x$ direction |
| $T_y$ | Moment about the $y$ axis |
| $T_z$ | Torque about the $z$ axis |
| $\hat{f}$ | Internal translational force in the $x$ direction |
| $\hat{T}_y$ | Internal moment about the $y$ axis |
| $\hat{T}_z$ | Internal torque about the $z$ axis |
| $\hat{f}_O$ | Internal translational force in the $x$ direction at point $O$ |
| $\hat{T}_O$ | Internal moment/torque about the $z$ axis at point $O$ |
| $\hat{\mathbf{f}}_0$ | Internal force vector at connection point coordinates |
| $\tilde{\mathbf{H}}$ | Receptance matrix of beam $AOB$ |
| $\mathbf{H}$ | Receptance matrix of parent structure $SO$ |
| $\tilde{H}_{ij}$ | Receptance of beam $AOB$ between coordinates $i$ and coordinate $j$ |
| $H_{ij}$ | Receptance of parent structure $SO$ between coordinates $i$ and coordinate $j$ |
| $H_{ij}^{\text{measured}}$ | Measured Receptance of assembled structure between coordinates $i$ and coordinate $j$ |
| $\widehat{\mathbf{H}}$ | Torsional receptance matrix of beam $OD$ |
| $E$ | nominal Young's modulus |
| $\breve{E}$ | Young's modulus with uncertainties |
| $\alpha$ | Percentage of uncertainty |
| RAN | A random value between 0 and 1 |
| $\rho$ | Density |
| $l_{AB}$ | Length of beam $AOB$ |
| $h$ | height of beam $AOB$ in the $z$ direction |
| $A_{\text{me}}$ | receptance without noise |
| $\breve{A}_{\text{me}}$ | receptance with noise |

only the angular displacements of one or more points of a shafting without knowing accurately the value of torque excitation. Usually, angular velocity of shafting structures is measured by means of slotted discs, gears or magnetic pickups [5,6]: one impulse is generated and detected once for every certain fraction of rotation of the shafting. Other similar devices such as grids or strips on the shaft as the target or rotary incremental encoders being installed at the free end of a shafting are also utilized [7]. For such a kind of measurement, a sufficient number of uniformly spaced teeth are of vital importance to maximize signal-to-noise ratios from the pickups. Optical methods involving lasers and the Doppler principle for angular vibration measurement [2,8] are gaining acceptance as the standard means of measuring torsional vibration due to their merits over previously mentioned methods.

Although several techniques have been proposed for measuring rotational FRFs, few are proposed or applied for measuring torsional FRFs. A pair of matched conventional linear accelerometers placed a short distance apart on a structure to be measured, or on a fixture attached to a structure are often utilized for measuring rotational FRFs [4]: the translational and angular displacements of a structure at the centre point between these two accelerometers can then be deduced. Duarte and Ewins [9] gave a comprehensive table showing several studies done for measuring rotational degrees of freedom and proposed one improved close-accelerometers method by considering residual compensation. When it turns to torque measurement for torsional vibration of shafting, strain-gauge rosettes are usually utilized. For transferring signals from strain-gauge rosettes, a slip ring or telemetry is commonly required [5]. For rotating structures, hydraulic torsional exciter and electromagnetic exciter systems are always introduced to apply a dynamic torque. Sihler [10] presented a novel exciter for applying a dynamic torsional force to a rotating structure which can be easily applied in cases where a three-phase electrical machine is contained in a shaft assembly. Kim et al. [11] investigated the possibility of non-contact modal tests for torsional vibration of cylindrical bodies like pipes by an electromagnetic exciter.

However, in the literature about torsional vibration tests, studies of methods for measuring torsional receptance are rarely reported, even though this information is very useful in practice and actual measurement is known to be error-prone. This lack of information suggests that development of an effective method for measuring torsional receptance is necessary. In engineering design stage, theoretical models are always used for evaluating the torsional vibration characteristics of a shafting system. For a shafting system, some parameters (for examples, inertias of electrical machines and dynamic stiffness of couplings) cannot be obtained easily or even obtained at all, especially when these parts are assembled. Consequently, the theoretical torsional vibration model of a shafting is very likely to have a poor accuracy. Torsional vibration measurement is then needed to validate or update the model. Measured vibration data is vitally important if a finite element model needs to be updated successfully [12]. Instead of updating a theoretical model, experimental data can also be used to construct a modal model of a structure or even used for fault identification of rotor systems [13–17]. Ricci et al. [18] updated their torsional vibration model of an industrial steam turbo generator based on only measured torsional natural frequencies. Pennacchi et al. [19,20] used a modal representation of the supporting structure for a rotating machine to increase the accuracy of fault identification. When restricted by the measurement technology, identification of parameters would be very difficult. Prediction of dynamic behaviour of a shafting based on such a theoretical model is not very accurate, let alone