Chapter 48
Tutorial: Bolted Joints and Tribomechadynamics

M. R. W. Brake

Abstract The mechanics of jointed structures is a challenging research area that necessitates collaboration from multiple disciplines. Traditionally, jointed structures have been studied in isolation by three major fields – structural dynamics, contact mechanics, and tribology. The foundation of the field of tribomechadynamics is in the notion that collaboration between these three fields is necessary to advance the state-of-the-art for joint modeling. In this tutorial, the state-of-practice, state-of-the-art, and cutting edge research for joint mechanics is presented.

Keywords Joint mechanics · Tribomechadynamics · Structural dynamics · Contact mechanics · Tribology

48.1 Introduction

The primary function of a joint in an engineering structure is to connect two separate substructures. This function, however, introduces a secondary function in which the joint changes the dynamics of an assembled system. With a sufficiently large excitation, a joint will cause the resonant frequencies to decrease and the damping ratios to increase for each mode. In some systems, the excitation necessary to see this nonlinear dynamic behavior is well outside of the operating regime for the system; however, for other systems, the nonlinear dynamics of the interface can result in a 5% change in frequency and a 200% change in damping ratio for a typical range of excitations. State-of-the-art techniques can predict the *linear* stiffness of a joint reasonably well (to within 10%); however, the frequency shift exhibited as the joint is exercised by larger forces as well as the amplitude dependent damping is beyond predictive capabilities. Consequently, the prediction of damping in structures (not just from joints) is the least well characterized part of a model in structural dynamics despite it being critical to the prediction and understanding of the behavior of a structure [1]. Therefore, the goal of joint mechanics research is to understand what excitation regimes will result in a linear joint behavior or a nonlinear joint behavior, and to be able to make meaningful predictions for the stiffness and damping introduced by a jointed interface.

Friction and mechanical joints have been investigated for, conservatively, 4000 years. Evidence in ancient hieroglyphics indicate that even in 2000 BC there was an understanding of the effects of lubrication in frictional system. Despite this, *predicting* the response of an assembled structure remains an elusive goal. One reason for this is that friction is, inherently, multidisciplinary in nature. To more fully understand the fundamentals of friction and its role in assembled structure, it is necessary to study tribology, contact mechanics, and structural dynamics amongst other fields.

Tribology, contact mechanics, and structural dynamics are three sub-disciplines of mechanical engineering that are each concerned with the study of interfaces in mechanical systems. Despite this, these three sub-disciplines have remained separate due to length scale considerations, solution techniques, and response metrics. As a result, common problems solved within one of these sub-disciplines rarely affects research within the other sub-disciplines. To address this, the field of Tribomechadynamics was founded to bridge the scales from the nano- and micro-structural characterizations of tribology to the macroscale modeling of structural dynamics. The goal of this new field is three fold: to develop predictive models of jointed structures that can be used to affect the design phase of a product, to predict the degradation of an interface over time due to wear/fretting, and to enable the optimization of jointed structures to reduce weight, be wear resistant, or have advantageous properties.

M. R. W. Brake (✉)
William Marsh Rice University, Houston, TX, USA
e-mail: brake@rice.edu

G. Kerschen (ed.), *Nonlinear Dynamics, Volume 1*, Conference Proceedings of the Society
for Experimental Mechanics Series, https://doi.org/10.1007/978-3-319-74280-9_48

48.2 Experimental Considerations

Until recently, it was difficult to discern trends in experimental data for jointed structures as the influence of the nonlinearities within a system were smaller than the experimentally measured variability [7, 8, 12, 33]. Recent experimental programs have shown that by developing a strictly controlled experimental procedure that minimizes operator-to-operator induced experimental variability, the nonlinear characteristics of a jointed structure can be accurately characterized. With this perspective, recent research has focused on the role of interfacial geometry [12] and contact pressure [28] on the dynamics of jointed structures. Aiding this effort has been the development of a set of benchmark structures (for instance, the Brake-Reuß beam [7, 8, 33], the Gaul resonator and the dumbbell apparatus [15, 32], and many others [25]). In addition, the development of nonlinear system identification techniques have allowed for a more sophisticated treatment of experimental data in order to characterize the response of a jointed structure [2, 11, 13, 19, 20]. With this high pedigree of data now available, the foundation exists for the modeling of jointed structures:

48.3 State of Practice

There are three common methods for modeling jointed interfaces in practice: linear springs, Coulomb friction, and Jenkins elements. These three common methods represent incremental increases in complexity and fidelity for modeling a jointed interface.

48.3.1 Linear Spring Models

A linear spring approach neglects all dissipation within a joint. If viscous damping is added in parallel to the linear spring, introducing a Kelvin-Voight viscoelastic model, this would be fairly representative of a joint in the linear regime [36]. Alternatively, a more common practice is to use modal damping to represent the dissipation seen in the linear regime of a joint's response [10]. These models, fundamentally, do not capture the correct physics for energy dissipation within a joint. Instead, they are the coarsest method to model a structure and are only applicable to linear systems in which the joint is not appreciably exercise.

48.3.2 Coulomb Friction

A second approach is to use high fidelity modeling and Coulomb friction between the two surfaces in an interface. It is tempting to think that a sufficient refinement of the interface will result in a converged model that can accurately predict the energy dissipation measured in an experiment; however, Coulomb friction has been shown to not be applicable to joint mechanics [32] as the three major assumptions behind Coulomb friction all break down (i.e. friction is linearly proportional to normal force, independent of contact area, and independent of damping). While this approach may be satisfactory for low consequence applications, the lack of conservatism in predictions made using Coulomb friction models can result in potential failures for high consequence applications, which should be avoided at all cost.

48.3.3 Jenkins Elements

The Jenkins element [14, 18], also known as an elastic slider, is a spring in series with a Coulomb friction element. The presence of the spring allows for phenomena such as microslip (i.e. the sliding of one portion of the interface while the remainder of the interface remains stuck) and interfacial stiffness to be represented in a coarse manner. One challenge with using a Jenkins element approach is that calibration can be prohibitively expensive when there are hundreds or thousands of contact pairs within an interface [21]. Nonetheless, of the three state-of-practice methods, this is the most suitable to capturing both the linear and nonlinear dynamic behavior of a jointed interface.

48.4 State of Art

As with all methods to be discussed, current approaches to modeling jointed interfaces are not predictive. Instead, the parameters within a model must be calibrated to match existing experimental data. In some instances, this can result in a prohibitively expensive analysis [21], and in all instances to date, this still cannot yield a model that is accurate for more than several modes of a structure. Several state-of-the-art approaches attempt to more accurately describe a jointed structure's behavior:

48.4.1 Iwan Models

The Iwan model, most commonly put forth in [30], attempts to describe the hysteretic behavior of a joint using a single nonlinear degree of freedom. Internal to an Iwan model is a finite set of Jenkins element that each have their own set of properties governing their stiffness and transition to slipping. This "whole joint" modeling approach is designed to capture both the amplitude dependent damping and stiffness of a joint. While there have been several perturbations on the Iwan model [17] since its application to joints (e.g. [6, 26, 34]), these models are not yet predictive. Typically, Iwan models take several parameters for their description, which usually include [30] the tangential stiffness of the interface, the force necessary to induce macroslip (i.e. the rigid body motion between two surfaces), and descriptions of how the dissipation changes with excitation amplitude. In general, these parameters are not straight forward to measure, which has resulted in the Iwan model not being widely adopted. Three recent extensions of the Iwan model are worth noting: modal Iwan models [26] (in which an Iwan model is fit to each mode for a quasi-linear response), the five parameter Iwan model [34] (in which the ratio of static and dynamic sliding is found to allow more flexibility in fitting experimental data), and the RIPP model [6] (which is an analytical representation of an Iwan element to allow for improved numerical properties and solution).

48.4.2 Bouc-Wen Models

Iwan models belong to a larger family of models termed Masing models [22, 29, 31]. A second category of Masing models, termed Bouc-Wen models [4, 35], are also hysteretic models. Unlike Iwan models, which are described as a series of elastic sliders, the Bouc-Wen models are described as a set of differential equations. It is hypothesized that any Iwan model can be represented as a Bouc-Wen model, and vice versa. The appeal of Bouc-Wen models is that they have more flexibility in representing other features of jointed interfaces (such as evolution over time [3]). However, very little work has been done to apply Bouc-Wen models to jointed structures [16]. Directly assessing the suitability of Bouc-Wen models to jointed structures, [23] compared a Coulomb friction model (assumed to be the "truth" data), Jenkins elements, and a Bouc-Wen model and found that the Bouc-Wen model was only capable of representing the hysteresis loop in an aggregate manner, whereas the Jenkins models are able to reproduce the hysteresis loop from the FEA simulations at all points throughout a loading cycle. The Bouc-Wen model was also found to exhibit a delay in the onset of microslip and decrease in contact stiffness.

48.5 Concluding Remarks

As researchers seek to find a method to represent a jointed structure more accurately and to predict the response, there are several open areas of research:

48.5.1 The Surrogate System Hypothesis

The Surrogate System Hypothesis [5, 9] states that a surrogate structure that contains the same joint as the system of interest can be used to deduce the properties of the joint. These properties, once accounting for the properties of the surrogate structure, can then be substituted directly into the system of interest as a spatially discrete joint model (as opposed to a modal model). The surrogate structure itself could be a system that is significantly easier or cheaper to manufacture than the application system. Ongoing work is seeking to validate this hypothesis and to determine its domain of applicability.

48.5.2 Coupled Normal Contact

Recent work has demonstrated that the normal contact within an interface is not constant [28], and, in fact, clapping mode behavior can be found even in tightly clamped lap joints. Most existing models, however, do not allow for flexibility within an interface. Thus, the next generation of joint models must include the local kinematics, particularly the coupling between normal and tangential contact. The three dimensional friction elements [24, 27] are a step in this direciton; however, they must be extended to include hysteretic damping.

References

1. Akay, A.: Research needs and open questions in vibration energy transport and dissipation. Technical report. National Science Foundation (2016, Forthcoming)
2. Allen, M.S., Mayes, R.L.: Estimating degree of nonlinearity in transient responses with zeroed early-time fast fourier transforms. Mech. Syst. Signal Process. **24**, 2049–2064 (2010)
3. Barber, T.T., Noori, M.N.: Modeling general hysteresis behavior and random vibration application. ASME J. Vib. Acoust. Stress Reliab. Des. **108**, 411–420 (1986)
4. Bouc, R., Forced vibration of mechanical systems with hysteresis. In: Proceedings of the Fourth Conference on Non-Linear Oscillation, Prague (1967)
5. Brake, M.R.W. (ed.): The Mechanics of Jointed Structures. Springer (2017)
6. Brake, M.R.W.: A reduced Iwan model that includes pinning for bolted joint mechanics. Nonlinear Dyn. **87**, 1335–1349 (2017)
7. Brake, M.R., Reuß, P., Segalman, D.J., Gaul, L.: Variability and repeatability of jointed structures with frictional interfaces. In: 32nd International Modal Analysis Conference (IMAC XXXII), Orlando (2014)
8. Catalfamo, S., Smith, S.A., Morlock, F., Schwingshackl, C., Reuß, P., Brake, M.R.W.: Effects of experimental methods on the measurement of a nonlinear system. In: 34th International Modal Analysis Conference (IMAC XXXIV), Orlando (2016)
9. Cooper, S.B., Rosatello, M., Mathis, A., Johnson, K., Brake, M.R.W., Allen, M.S., Ferri, A.A., Roettgen, D.R., Pacini, B.R., Mayes, R.L.: Effect of far-field structure on joint properties. In: 35th International Modal Analysis Conference (IMAC XXXV), Garden Grove (2017)
10. Deaner, B.J., Allen, M.S., Starr, M.J., Segalman, D.J., Sumali, H.: Application of viscous and Iwan modal damping models to experimental measurements from bolted structures. ASME J. Vib. Acoust. **137**, 021012 (2015)
11. Dossogne, T., Noël, J.P., Kerschen, G.: Robust subspace identification of a nonlinear satellite using model reduction. In: 34th International Modal Analysis Conference (IMAC XXXIV), Orlando (2016)
12. Dossogne, T., Jerome, T.W., Lancerau, D.P.T., Smith, S.A., Brake, M.R.W., Pacini, B.R., Reuss, P., Schwingshackl, C.W.: Experimental assessment of the influence of interface geometries on structural response. In: 35th International Modal Analysis Conference (IMAC XXXV), Garden Grove (2017)
13. Feldman, M.: Hilbert transform in vibration analysis. Mech. Syst. Signal Process. **25**, 735–802 (2011)
14. Gaul, L., Nitsche, R.: Friction control for vibration suppression. Mech. Syst. Signal Process. **14**, 139–150 (2000)
15. Gaul, L., Nackenhorst, U., Willner, K., Lenz, J.: Nonlinear vibration damping of structures with bolted joints. In: 12th International Modal Analysis Conference (IMAC XII), Honululu (1994)
16. Ismail, M., Ikhouane, F., Rodellar, J.: The hysteresis Bouc-Wen model, a survey. Arch. Comput. Meth. Eng. **16**, 161–188 (2009)
17. Iwan, W.D.: A distributed-element model for hysteresis and its steady state dynamic response. ASME J. Appl. Mech. **33**, 893–900 (1966)
18. Jenkins, G.M.: Analysis of the stress-strain relationships in reactor grade graphite. Br. J. Appl. Phys. **13**, 30–32 (1962)
19. Kerschen, G., Worden, K., Vakakis, A.F., Golinval, J.C.: Past, present and future of nonlinear system identification in structural dynamics. Mech. Syst. Signal Process. **20**, 505–592 (2006)
20. Kurt, M., Chen, H., Lee, Y.S., McFarland, D.M., Bergman, L.A., Vakakis, A.F.: Nonlinear system identification of the dynamics of a vibro-impact beam: numerical results. Arch. Appl. Mech. **82**, 1461–1479 (2012)
21. Lacayo, R.M., Pesaresi, L., Fochler, D., Groß, J., Brake, M.R.W., Schwingshackl, C.: A numerical round robin to predict the dynamics of an experimentally-measured brake-reuss beam. In: 35th International Modal Analysis Conference (IMAC XXXV), Garden Grove (2017)
22. Masing, G.: Self-stretching and hardening for brass. In: Proceedings of the Second International Congress for Applied Mechanics, pp. 332–335 (1926)
23. Oldfield, M., Ouyang, H., Mottershead, J.E.: Simplified models of bolted joints under harmonic loading. Comput. Struct. **84**, 25–33 (2005)
24. Petrov, E.P., Ewins, D.J.: State-of-the-art dynamic analysis for non-linear gas turbine structures. Proc. Inst. Mech. Eng. G: J. Aerosp. Eng. **218**, 199–211 (2004)
25. Peyret, N., Dion, J.L., Chevallier, G., Argoul, P., Micro slip induced damping in planar contact under constant and uniform normal stress. Int. J. Appl. Mech. **2**, 281–304 (2010)
26. Roettgen, D.R., Allen, M.S.: Nonlinear characterization of a bolted, industrial structure using a modal framework. Mech. Syst. Signal Process. **84**, 152–170 (2017)
27. Schwingshackl, C.W., Di Maio, D., Sever, I., Green, J.S.: Modeling and validation of the nonlinear dynamic behavior of bolted flange joints. ASME J. Eng. Gas Turbines Power **135**, 122504–1–8 (2013)
28. Seeger, B., Butaud, P., Du, F., Baloglu, V., Brake, M.R.W., Schwingshackl, C.W.: In situ measurements of interfacial contact pressure during impact hammer tests. In: 36th International Modal Analysis Conference (IMAC XXXVI), Orlando (2018)
29. Segalman, D.J.: An initial overview of Iwan modeling for mechanical joints. Technical report SAND2001-0811. Sandia National Laboratories, Albuquerque (2001)

30. Segalman, D.J.: A four-parameter Iwan model for lap-type joints. ASME J. Appl. Mech. **72** 752–760 (2005)
31. Segalman, D.J., Starr, M.J.: Iwan models and their provenance. In: ASME International Design Engineering Technical Conferences IDETC/CIE, Chicago (2012)
32. Segalman, D.J., Gregory, D.L., Starr, M.J., Resor, B.R., Jew, M.D., Lauffer, J.P., Ames, N.M.: Handbook on dynamics of jointed structures. Technical report SAND2009-4164. Sandia National Laboratories, Albuquerque (2009)
33. Smith, S.A., Bilbao-Ludena, J.C., Catalfamo, S., Brake, M.R.W., Reuß, P., Schwingshackl, C.: The effects of boundary conditions, measurement techniques, and excitation type on measurements of the properties of mechanical joints. In: 33rd International Modal Analysis Conference (IMAC XXXIV), Orlando (2015)
34. Wang, X.Q., Mignolet, M.P.: Stochastic Iwan-type model of a bolted joint: formulation and identification. In: 32nd International Modal Analysis Conference (IMAC XXXII), Orlando (2014)
35. Wen, Y.K.: Method for random vibration of hysteretic systems. ASCE J. Eng. Mech. Div. **102**, 249–263 (1976)
36. Yang, J.N., Lei, Y., Pan, S., Huang, N.: System identification of linear structures based on Hilbert-Huang spectral analysis. Part 1: normal modes. Earthq. Eng. Struct. Dyn. **32**, 1443–1467 (2003)